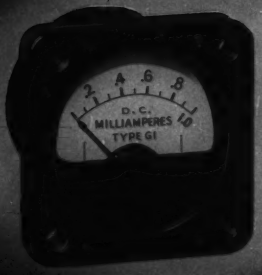
ELECTRICAL ENGINEERING

PUBLISHED MONTHLY BY THE AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS



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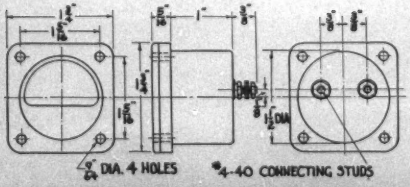

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War shortages crop up in strange materials. Mica, for instance. Once seen principally in the windows of stoves, and in small boys' pockets, it is now used extensively as electrical insulation. In some war products, it is virtually indispensable: capacitors for radio, spark-plugs for airplane engines, insulators in electronic tubes.

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The War Production Board, convinced that much mica was classified too low when judged by appearance alone, asked Bell Telephone Laboratories to develop a new method of electrical tests. The Laboratories were able to do this quickly and successfully because of their basic knowledge and experience in this field.

The new tests were made available to manufacturers in this country and abroad—the supply of usable mica was increased 60% — and a difficult situation relieved.

Skill to do this and other war jobs is at hand in Bell Laboratories because, year after year, the Laboratories have been at work for the Bell System.

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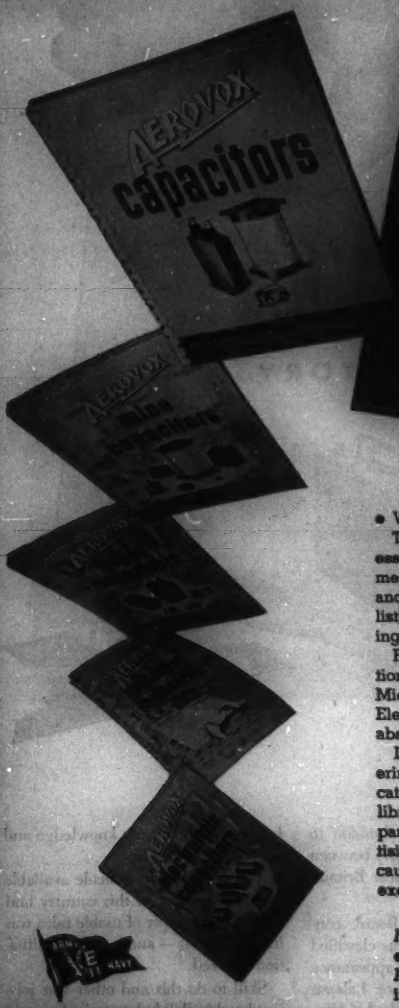
February 1945, Vol. 64, No. 2. Number of copies of this issue 27,350

Here's an ESSENTIAL TOOL for Radio-Electronic Engineers, Designers, Equipment Builders, Manufacturers...



• Why essential? That's a big statement. Let us qualify:

This new Aerovox Catalog contains that information which is essential to those who design and build radio-electronic equipment. Here is general and specific engineering data on capacitors and their applications; detailed specifications on various types; listings of recommended types and ratings; special notes covering special features and special types; color codes; etc.

For greater convenience, the catalog is divided into four sections, each with its tab-indexed cover. These sections comprise Mica Capacitors, Application Engineering Data, Paper Capacitors, Electrolytic Capacitors. The plastic binding permits pages to lie absolutely flat.

In preparation for a year and a half—involving widespread gathering of data and intensive compilation—this combination manual-catalog represents an outstanding contribution to the working library of the radio-electronic engineer and executive. It was prepared BY engineers FOR engineers; contains absolutely no advertising—just information on capacitance and capacitors. And because of cost, its circulation is strictly limited to engineers and executives.

• Write for Your Copy...

If you are engaged in designing or building radio-electronic equipment of recognized standing, write on your business letterhead for your registered copy. Also submit your capacitor problems and requirements for our collaboration.

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OKOSHEATH PROTECTIVE COVERING is impervious to all corrosive agents likely to be encountered in underground ducts.

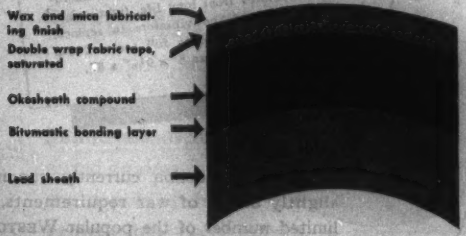
It possesses good electrical insulating properties. Insulation resistance measurements between lead sheath and ground have proved its permanent electrical insulating quality. Particularly desirable for use on large size single conductor cables which are likely to have heavy sheath currents.

Okosheath prevents mechanical injuries to the lead sheath that are impossible to avoid completely when handling and pulling. These are the points at which both corrosion and fatigue become concentrated.

FIELD TEST

A 150-foot length of Okosheath covered cable was installed in a standard duct system. This test length has been periodically removed from the ducts and reinstalled after careful examination and tests. Today, after more than ten years, the Okosheath Protective Covering is still in excellent condition although the outer fabric tapes show some deterioration because of the excessive pulling in and out of the duct.

Enlarged cross-section view of Okosheath Protective Covering



Natural rubber was generally used in the Okosheath compound until the shortage in our rubber supply occurred. Now Buna S synthetic rubber or Okoprene (made with neoprene) is used in the Okosheath compound. Tests indicate that results with Buna S or Okoprene are comparable with those of natural rubber. Okoprene is preferable because of its superior oil resistance and nonflammable quality while costing no more. The Okonite-Callender Cable Company, Inc. Executive Offices: Passaic, New Jersey.

Okosheath Quick Quiz

Q. What about cost?

A. Okosheath Covering is relatively cheap corrosion insurance. For a standard 3-conductor, 350,000 CM, 15,000-volt paper-insulated lead covered cable, the Okosheath covering adds about 20% to the cost.

Q. Is this expensive?

A. Not when you consider that Okosheath covering need only be applied in sections where corrosion is known to exist. Compare it with the cost of a single lead sheath failure which involves the following items: locating trouble, withdrawing the defective faulty length, supplying a new cable, pulling in the new length and splicing it. This does not even consider revenue loss due to service interruptions.

Q. How much is the cable diameter increased?

A. Okosheath jackets are about 1/8" thick and add approximately 0.250" to the cable diameter.

Q. Is the current-carrying capacity of the cable adversely affected by the Okosheath Covering?

A. No, because of the increase in surface area.

Lead sheathed cable with Okosheath Protective Covering.

OKONITE-CALLENDER

paper insulated power cables

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with these versatile WESTON Test Instruments

The Multi-Purpose, Super-Sensitive Analyzer

(MODEL 772)

A compact and practical wide-purpose instrument with sensitivity of 20,000 ohms per volt, on dc ranges.

volt, or 1000 ohms per volt, on ac ranges.

Voltage, a-c and d-c — 0-10/1 amps. — 0-250/50/10/1 milliamps. and 100 microamps.

Current, d-c — 0-1000/250/50/10/2.5.

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(Voltages up to 5000 dc available through use of external WESTON Televerter, Model 766.)

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Recognized as the most complete unit for routine maintenance tests, and for testing needs which require an ultra-sensitive instrument.

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With production currently running slightly ahead of war requirements, a limited number of the popular WESTON test instruments shown herewith are available and are offered subject to prior sale. Orders can be placed direct, or with the WESTON representative in your vicinity. Literature available from...WESTON Electrical Instrument Corporation, 664 Frelinghuysen Avenue, Newark 5, New Jersey.

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HARVEL 612-C

DOES NOT SUPPORT FUNGUS GROWTH*

Photograph Illustrates the fungus resistance of Harvel 612-C Clear Baking Varnish. Note that the fungus culture of chaetomium globosum has not attacked the sample film of Harvel 612-C.

Fungus Resisting Properties protect electrical equipment

Electrical equipment operating in humid atmospheres, must be protected against the constant danger of the attack of fungus growth. This growth has been known to cause failure of electrical units within a few hours under severe tropic conditions.

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Where an air-drying fungus resistant varnish is desired, use Harvel 902-F. This type, like Harvel 612-C, does not support fungus growth.

Complete information and a free sample of either Harvel 612-C or Harvel 902-F varnish will be sent on request. Write Dept. 16.

*Tested by the U. S. Testing Laboratories in accordance with A. S. T. M. Specification D484-42T.

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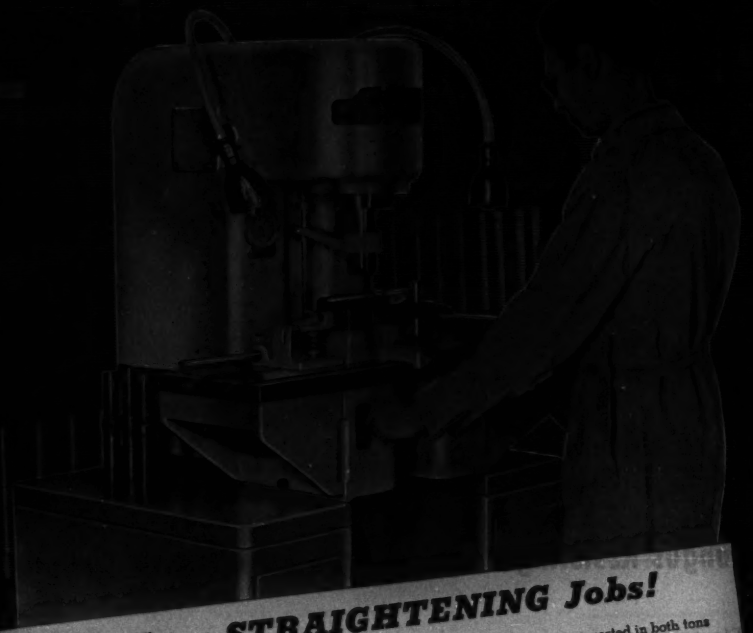

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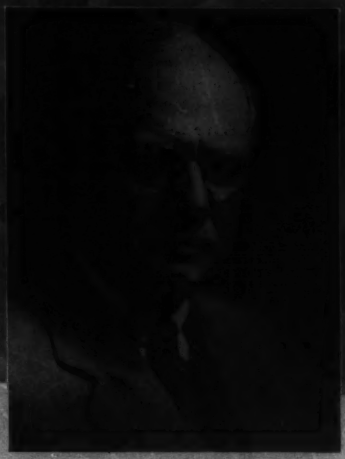

A few comments based on the first 50 years of the JAMES G. BIDDLE COMPANY

BUSINESSES, like people, usually have distinct, individual personalities. The smaller the business, the more clearly it will reflect the character of the man who built it.

In 1895, when the electrical industry was in its infancy, James G. Biddle went into business as a manufacturer's agent, selling electrical measuring instruments and scientific apparatus. One of his basic aims in the conduct of the business was to be more than a mere source of supply. He decided to provide a service that was outstanding by reason of its alert, interested, personal character. This aim has never been changed by Mr. Biddle or his associates during the last half century. It will continue to be an important factor in the policies of the James G. Biddle Company in the years to come. We are committed to this.

•

In celebration of our 50th anniversary, we have prepared a brief booklet entitled "Report at Mid-Century." It touches upon interesting points regarding the growth and advancements of the electrical field in general and our business in particular. We would be pleased to send you a copy upon request.

JAMES G. BIDDLE CO. • 1211-13 ARCH STREET • PHILADELPHIA 7, PENNA.

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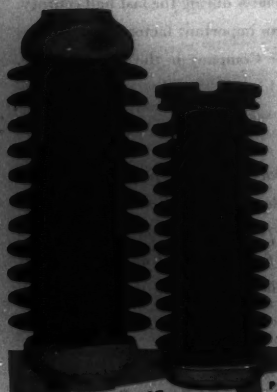

Lapp

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LAPP LINE POST and STATION POSTS on your system offer . .

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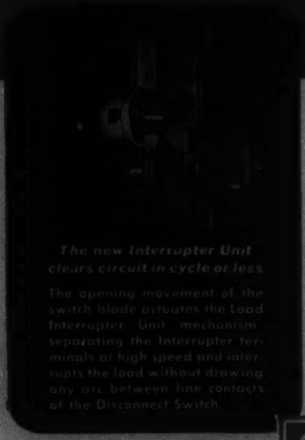
NO CLEANING. Fog-type design preserves uniform leakage path, prevents leakage flashovers, makes the unit "self-cleaning."

MECHANICAL RUGGEDNESS. Stones or bullets deflect off, or rupture petticoats, leaving post body intact and insulator secure.

THIS IS THE TREND



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Today power company customer installations are being made with S & C Load Interrupter Disconnect and Power Fuse Combinations. Enclosed in steel cabinets, they occupy little space, are easy to install and maintain—yet provide thoroughly reliable short-circuit protection and *switching under load conditions* without drawing an arc external to the switch contacts.

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SCHWEITZER & CONRAD, INC.

4427 Ravenswood Ave., Chicago 40, U. S. A.

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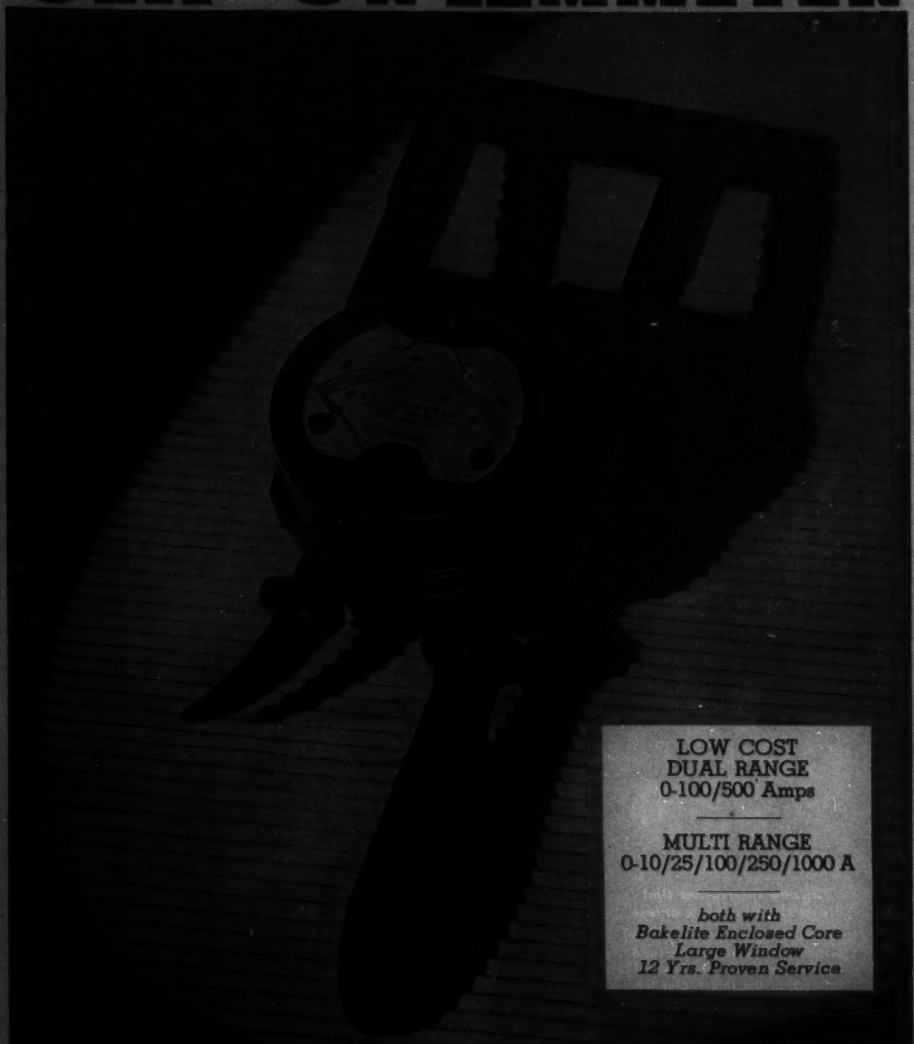
LOAD INTERRUPTER DISCONNECT SWITCH and FUSE COMBINATION

CLIP-ON AMMETER



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DUAL RANGE
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both with
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ELECTRICAL ENGINEERING

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FEBRUARY
1945

The Cover: Electric control equipment sails the seven seas in the "baby flat-top," a refitted cargo vessel.
Allis-Chalmers photo

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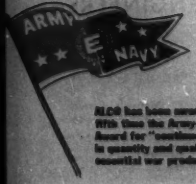
Typical designs taken from a roster of more than 25,000 distinct items are splendidly illustrated—in groups of applications covering electrical, electronic, industrial heating, chemical, automotive and other fields. Property charts and other technical data, together with practical information on manufacturing processes, are included.

Here is valuable, authentic information... the latest work on Ceramic insulators... in concise, easy-to-use form. If you have not received your complimentary copy of Bulletin No. 444, please write for it today.



ALSIMAG has been awarded for the fifth time the Army-Navy "E" Award for "continued excellence in quantity and quality of essential war production."

AMERICAN LAVA CORPORATION
CHATTANOOGA 5, TENNESSEE

ELECTRICAL ENGINEERING
VOLUME 64, NUMBER 2 FEBRUARY 1945

Technology in Postwar Expansion

WILLARD CHEVALIER

NOT so many years after photography was introduced to the world, George Eastman revolutionized the infant business by offering to do the developing of the negatives and the printing of the pictures in Rochester. He brought photography to the people with his slogan: "You press the button; we do the rest."

It seems that this slogan really should belong to the electrical industry, for the pressing of a button long has been the means of releasing electric energy for productive purposes. But when one reads of the progress made in electrical engineering in recent years, one realizes that this slogan "You press the button; we do the rest," already is a bit out of date. The trend in electricity seems to be to do away with the necessity of pressing a button or turning a switch. An electronic tube, quite likely, can be given that job and can start or halt the flow of electricity more rapidly and more efficiently than when this task is entrusted to human hands and brains.

The very mention of the word "electronics" lays open a vast field for speculation as to its particular part in the broader program for technology in the postwar world. Unfortunately crystal gazing has its disadvantages. The prophet who looks into his globe and sees electronics doing most of the work of the home and the factory of the future should have another crystal ball handy into which he could peer and determine the date upon which these developments will be available to the customers.

ENGINEERS HAVE REALISTIC APPROACH

Engineers have just as good imaginations as the best of the Sunday feature writers, but they have a more realistic approach to the time element involved. If engineers fail to act, we cannot have any of these new good things that have been promised us. However, engineers alone cannot give us these things—producing them will require the wholehearted co-operation of capital, labor, management, and the consumers.

The eventual consumer of electricity knows very little about it. Electricity is a mystery subject to the average person and so one hears some rather unusual ideas expressed about it from time to time. But because it is all about us, in so many forms, it is of extreme interest to the individual, and the more information, in nontechnical terms, about electricity that is made available to the average man, the better he will be able to understand the engineer's attitude and problems.

Gilbert D. McCann of the Westinghouse Laboratories explained recently, in simple terms, that the value of lightning was not in the amount of potential electric energy that might be harnessed, but in the fact that when lightning shoots earthward it releases nitrogen from the air. About 100,000,000 tons of nitrogen annually are absorbed into raindrops and fall to the earth, enriching the soil so that we may have food. More nourishment for the earth is provided by lightning than by all of the world's fertilizer plants. Information such as this, when given widespread circulation, tends to reduce the number of fantastic ideas that are offered to provide a world with "free energy" through the harnessing of the highly erratic power that all of us know *does exist* in lightning.

The job of education should extend beyond the field of electricity, however. There are just as many impractical notions afloat in the whole broad field of technology.

Maintaining production at a high level is the key to expanding the American standard of living and extending its benefits to more of the people in the postwar period, declares this author. If we keep open wide the doors of opportunity, security will take care of itself, he contends. The tasks that the postwar world poses are tasks in which engineers, as well as capital, labor, and management, all have their responsibility.

One of the most dangerous predictions about this bright new postwar world that technology and science can provide for us is that the final result will be less employment for the people. A report on a speech made by an Army officer recently pictured a postwar world with television sets, combination heaters and coolers for stable temperatures, plastic furniture and dishes, dustfree air in sealed homes, and beam-power transmission for low-powered electric devices. But, this speaker warned, these labor-saving devices will tend to create a critical unemployment situation. The one tenth of the population continuing to be employed and having all it needs will forget that the other nine tenths also must make a living, he said.

EMPLOYMENT A POSTWAR PROBLEM

Already we have seen some labor leaders going on record as favoring the 30-hour week as a means of spreading the work so that more people will have jobs in the postwar world. Too many are working on the theory that all of the new gadgets that have been promised us will be available with the defeat of Japan and that, as a result, there never will be enough jobs to go around.

But what are the facts? Let us look at a typical industry. Only once in the history of the automobile has that industry had an average 30-hour week. That was in 1932, when total payrolls in the automobile manufacturing field were the lowest they had been at any time since the start of the first World War. That was in 1932 when the average weekly earnings in the automobile industry were the lowest, except for the following year, of any year between the first World War and the present time. That was in 1932, when the number of motorcar registrations showed the greatest decline in the history of the automotive business, at least until production was completely shut off early in 1942.

It is true that we could put more men to work producing automobiles if we were to return to the production methods that existed back in the early part of this century. But would we have a market for automobiles so produced?

We may be able to find the answer from the experience of one of the pioneers in the automotive field. In 1908 it was pro-

Essential substance of an address made before the AIEE San Francisco Section, San Francisco, Calif., October 13, 1944.

Willard Chevalier is vice-president and director of McGraw-Hill Publishing Company, Inc., New York, N. Y., and publisher of *Business Week*. He served as lieutenant-colonel of the 11th United States Engineers during World War I.

ducing a limousine for $5,000, a very fine product for its day. But in 1937 it turned out a much finer car for $1,200, less than a quarter as much. Was this because of the greater skill of the workers? Quite probably those old-time automotive workers had a greater degree of hand skill than those who turned out the better and cheaper car in 1937.

INCREASED EFFICIENCY—DOUBLED OUTPUT

I think the more logical answer for this improved and cheaper product is found in the fact that this company recognized the necessity of increased efficiency and spent huge sums to install an assembly line. It purchased and built special tools and dies and jigs, and mammoth presses and hammers. Through this expenditure for new machines and improved methods the company was able to double the value of output for each worker between 1908 and 1937. And at the same time that the output was doubled, the annual wages of the workers were tripled.

The important thing to remember is that this increase in wages and a gradual lowering of the number of hours for the workers came as a result of producing not less, but more, thanks to the investment of additional capital in more efficient machines and methods. The actual return to investors probably showed little or no increase—it may even have shown a decline—between 1908 and 1937. But in those same years the return for the workers and for the customers was tripled and quadrupled.

We have seen that the automobile became an essential in our vast transportation system, not because we produced fewer automobiles, but because we produced more of them. It seems logical to assume, therefore, that those who forecast the doom of the American standard of living as a result of overproduction may be on the wrong track.

SEEK MEANS OF PRODUCING MORE

It would seem that, if we, as engineers, as automotive workers, or as laborers in any field, were seeking the solution of the problem of expanding the American standard of living and extending its benefits to more and more of the people, we should seek means of producing more. This makes sense, because only by *producing* more can we employ more men in useful jobs. Only by *producing more* can we have *more to sell*. Only when we have *more to sell* shall we have *more to distribute* in the form of wages to the worker. And to those who say: "But we must provide security for all," we can reply that if we keep open wide the doors of opportunity security will take care of itself.

In the final analysis, the only way we can insure greater security is to add more to the nation's stock of goods. This applies equally to the engineer, who creates; the capitalist, who invests to make ideas turn into actual products; and the worker, who operates the machine that makes the process possible. If we are agreed that we can make this a better world to live in by producing more, let us see what each of us shall have to do in order to achieve this better world.

WHAT IS FULL EMPLOYMENT?

The worker may say he is interested primarily in full employment. So, what do we mean by full employment? Full employment could mean that every man, woman, and child in the United States would have to be provided a job and presumably draw wages. Full employment could mean that every one would have to be on the job every minute. Even machines cannot keep that up forever. Even if we define full employment as meaning that every able-bodied person over a certain age shall be kept at work, I doubt very much if that is what we want. For the only way we can achieve such a degree of employment is to have a totalitarian government with the power to say: "You *must* work, and here is *where* you shall work; this is *what* you shall be paid, and this is *what* you shall produce."

As long as we remain a free people, and the individual is free to work or go fishing, as he may elect, or go into business for himself, or to work for another, or to tell one's boss off, and go down the street and look for another job—in short, if we are to remain free to find our own places in the national economy—we shall not have full employment in that sense.

Actually what the worker wants is a sustained high level of employment. He wants a level of employment so high that he will never have to fear that if he quits a job—for whatever reason—he will not be able to get another one as soon as he needs it.

The worker will want no full-employment plan that will prevent him from taking the summer off so he may load up the car and see America if he and his family desire. The worker will want no full-employment system that will prevent him from working hard all summer so that he may take it easy in the winter, if that happens to be his idea of the way to achieve happiness.

No mass-security plan is ever going to be popular in the United States if it limits the productivity of the man who wants to get ahead by working a little harder to that of the man without ambition.

HIGH LEVEL OF EMPLOYMENT

Capital also must seek a high level of employment if it is to fulfull its true mission in the postwar world. The day when capital can increase itself through manipulation of pieces of paper should be gone forever. If capital is to expect a return, capital must apply itself to truly productive effort. Capital must not seek security by protecting investments in machines or methods that *were* good. Capital must look for new machines and new methods that will produce more things at the same cost and better things at lower costs, for capital, like labor, must depend upon increased production and increased sales for its livelihood.

DUAL ROLE OF SCIENCE AND TECHNOLOGY

Science and technology have a dual role in the postwar expansion. Science, the creator, must work hand in hand with science, as represented by efficient management, if the wealth provided by capital and the work provided by labor are to be fruitful. The opportunities for technology in the field of creation appear to have no limits at the present time. What was regarded as impossible only a few years ago is now commonplace. Actualities in the postwar expansion may be only ideas today.

The United States and the Allied nations agree that our great war record would not have been possible had it not been for science and technology. But do we all realize that this great triumph on the battlefield is not the result of new scientific knowledge, but the result of the utilization of knowledge that has been accumulated since the first records were preserved.

Science is virtually unique in that it has no obsolescence problem. Stockholders in a factory may find it necessary to scrap machinery worth thousands of dollars and install new equipment, because a competitor down the street found a better way to turn out a product. Technology, in the process of creating new jobs, occasionally forces the closing of factories and workmen lose jobs and all contact with what went before. But science does not obsolete old knowledge as the new is acquired. Theories may be disproved and go into the discard, but facts and experience never wear out. Facts, discovered yesterday, are no more valuable than those known since the beginning of recorded history. The future of science, in fact, will depend not nearly so much on the discovery of new facts as on finding new applications of what is already known.

The world has been loud in its praises of the accomplishments of science as a means of speeding this war to a victorious conclusion. These accomplishments have been made possible, in many instances, because of the speeding up of research. Many of the products that went out of the laboratory directly to the battle front are five to ten years ahead of their normal time.

INDUSTRY INDEBTED TO RESEARCH

As industry faces the postwar period it will be able to take advantage of much of this war-inspired progress. Industry is going to get peacetime dividends from war. That is why industry has an obligation to put more back into scientific research so that there shall be no diminishing dividends in the future. On all sides we see indications that there are dangers ahead if this obligation is not met. Educators

point to the decline in enrollment of students in science as a result of the war. This means a decline in scientific research a few years hence, for researchers cannot be made overnight. Research workers worthy of the name must remain longer at the storehouse of knowledge than workers in many other fields, for researchers cannot dismiss the past as they look to the future. Research cannot obsolete old equipment when new equipment is available. Research can only add to its store of raw materials as the engineer and the inventer look for new ways to produce new things that the people will want and need.

ROLE OF SCIENCE IN MANAGEMENT

Science also must play its role in management, in providing for efficient use of the things that are created. Science in management is a comparatively new concept on the American scene. For many years the public was led to believe that the scientist and the engineer were types apart from the humdrum business world. But with the passing of the years there has been increased recognition of the fact that scientific treatment of day-to-day problems can and does result in more efficiency, which leads to more production, and to more jobs.

It is said that no other nation in the world today, has more men than we have in private and commercial laboratories engaged in planning for peace. We all know that new jobs are being discovered for electricity to do. This is good, for if science is not given a chance to work in behalf of all of the people we cannot achieve the highest possible production, the highest possible employment, and the highest possible efficiency. But science will not have served this country best merely by creating. It must take its place in management to help integrate the efforts of capital and labor with the technology it creates.

MANAGEMENT A FUNCTION—NOT A CLASS

It is unfortunate that to many people "management" has come to be synonymous with "employer." As a result these people see management and labor as natural antagonists and efficient management as meaning no more than additional profits in the pockets of the employers. Efficient management, of course, draws men from every walk of life, and every level of society. Management is not, in itself, a group or a class. Management is a function.

Ever since men began to work together to common ends, their chief problem has been to direct their efforts so they might obtain more of the things they wanted than would be possible if each had worked for himself alone. The solution of that eternal problem is the function of management.

Without management, the 5, the 50, the 5,000, or the 500,000 men and women who constitute any business enterprise might be milling about in futile activity—spending their energies, consuming their food, wearing out their clothes, using up their goods and tools—and, in the end, have nothing to show for it but their pains.

When you hear the statement, "Labor creates wealth," bear in mind that you have not heard the whole story. All labor consumes wealth, too. It is only directed labor—managed labor—that creates more wealth than it consumes.

Management has many duties. It must plan and provide the facilities needed to multiply the fruits of our labor. It must select and train those best qualified to work together. It must direct and supervise the day's work, always keeping in mind the relation of one day's activities to the master objectives. It must impose discipline—that is, it must have the authority to hold each individual to his share of the task. It must seek out markets and prevail upon others to want the product of its particular workers, in exchange for that of their own.

Under the original concept of engineering, its participation in management might end with the planning and the provision of the facilities. But in the electrical field, we all recognize the importance of engineering in providing efficient means for distribution of our products. Here engineering plays an important part in marketing.

FOREIGN TRADE IN POSTWAR EXPANSION

Electrical engineering is likely to play a still more important part in marketing in the postwar expansion, because foreign trade in the electric-equipment field is one of the many in which American manufacturers feel they may have an advantage. One reason for this is their ability to send out their salesmen in full confidence that they can back up the salesmen with technical superiority.

A recent survey by the Department of Commerce estimated that a foreign export trade of $7,000,000,000 can be realized in the postwar period. The department set the goal for electric-equipment export at $195,000,000 annually, divided roughly as:

Radio receiving and transmitting equipment, 17 per cent.

Generators, transformers, and so forth, 14 per cent.

Electric refrigerators, 12 per cent.

Electric motors and controls, 12 per cent.

The remainder in primary and secondary batteries, household appliances, and wiring and wiring devices.

France alone has a program involving the expenditure of some $270,000,000, designed to restore electric service in all towns with a population of more than 30,000. The Russians have announced a program calling for 559 generating stations totalling 2,706,000 kw.

A more recent private survey says the $195,000,000 export business in electric equipment may be overoptimistic, but agrees that the figure *can be reached* if American businessmen make a *vigorous effort* to attain it. Even if the total reaches only $165,000,000, it will be 30 per cent greater than in 1929 and 60 per cent above 1939. It would appear there is an unequaled opportunity to build enduring trade relationships.

NEW USES FOR MOBILE POWER PLANTS

At least two of the major electrical manufacturing firms in the United States are now producing mobile electric-power plants of 3,000 to 5,000 kw capacity. Such plants are being purchased by the Soviet Government and by our own military forces to serve communities while sabotaged power plants are being rebuilt.

It is quite probable that new uses for mobile power plants will be found after the work of rebuilding Europe has been completed. Certainly there is reason to believe that application of inventiveness and engineering ingenuity will result in opportunities for practical applications of mobile power within the United States.

ELECTRICAL ENGINEERING IN AVIATION

We are all familiar with the importance of electrical engineering and design in the aviation industry. A recent report said that in 1932 radio and communication represented 20 per cent of the total expense of commercial aircraft maintenance and operation. Now it represents 60 per cent of the total.

Midget motors operating at frequencies higher than the accepted 60 cycles have proved desirable in airplanes, because they can be made smaller and lighter than the conventional models of only a few years back. There is talk now about electric drives for airplane propellers, with generators in the fuselage and the transmission of power to small motors that would permit more efficient streamlining. This is not practical yet, but electrical engineers and metallurgists have a challenge here. They face the problem with the realization that airplane designers approve the idea of a central power plant, instead of two or four in the wings, because it would help them produce a better-balanced airplane. But at high altitudes electricity performs differently than it does at sea level. As air density decreases, destructive arcs develop at lower voltage. Operation of airplanes in the tropics and in the arctic, at sea level and at high altitudes as a result of the war certainly has helped to solve some of the problems of heat, cold, and humidity that would have baffled us as late as 1941.

MYSTERY OF ELECTRONICS

There is considerable mystery about electronics, among electrical men; their place in the postwar world is not a secret just because military secrecy has forced us to be quiet about certain applications. There are many instances of manufacturers

being refused knowledge of the use to which certain apparatus is being placed, because the inventer wants to keep his secret.

SECRET FORMULAS OF EARLY DAYS

A small rubber manufacturer said recently that the business secret was the principal stock in trade of some of the rubber manufacturers in the early days. Spies were sent into plants in the hope of obtaining the secret formula. Gradually certain manufacturers agreed to exchange information, in the hope of improving their own products and found that, often, they had been guarding the same secret. The war brought an acute rubber shortage, and further interchange of information became essential if we were to survive. Technicians from the major companies went into small plants, and owners of small plants were welcomed to the major factories. They found that the "secret formula" was not the true secret but what one did with a formula, based on fundamental laws of chemistry and physics, was what really counted.

For many years the photoengravers prided themselves on the secrets they held in the various phases of the process of converting a photograph into a zinc or copper plate, from which thousands of copies could be printed. There was no such thing as an all-around engraver. There was the camera man, the developer, the etcher, the re-etcher, each with his own little bag of tricks. Then one day an enterprising promoter developed a one-man engraving plant after somehow managing to acquire enough basic formulas to permit him to put a comparatively inexperienced man in charge of it. Before the war came on, scores of small newspapers about the country that, under no circumstances, could afford the four or five men required to operate the old-style engraving plant started turning out local pictures, because they *could afford* one man to run the whole show, and possibly act as staff photographer, in addition.

APPLICATIONS OF ELECTRONICS

There has been considerable publicity on the use of electronic heat in speeding of production of penicillin, new wonder drug needed by our Armed Forces and civilians alike. There have been forecasts that electronic heat some day may be used to dehydrate foods on a commercial basis; that it will help to cook our postwar steaks. But a good many applications of electronics, in heating and in motor and machine control, are still being produced on a custom-built basis to individual specifications. The result is that the manufacturers are unable to turn out a packaged product in sufficient volume to permit widest possible application and to get prices down to the lowest possible level. Whether the future of electronics will be hampered because of wide application of the "business-secret" theory is still to be determined.

It seems that the future of the engineer in electronics, or in any other phase of the application of electricity to productive purposes, depends on just two things:

1. How alert his firm is in recognizing that it can never be satisfied with a good thing, even if it thinks it is the only firm that has it.

2. How alert the engineer is to the necessity of adding to his store of knowledge and finding new applications for what he already knows.

No firm can afford to stand still. If it is not always working on a program to obsolete what it has and to produce something better, or cheaper, it may rest assured that the competitor down the street, or across the nation, is doing that very thing. No engineer can be satisfied merely by bringing himself up to date on the developments in the field of electricity. He must not, in fact, confine himself to electricity. He must search out opportunities to apply the potentialities of electricity to fields that are not now even considered within the realm of his activities.

Electricity, and technology as a whole, have made rapid strides in recent years. But there can be no resting on the oars now. The American people expect still greater things in the future, and they will expect engineers to assume their full share of the task of providing a postwar world that is geared to high-level production, with its attendant high-level employment. This can be made possible only by high-level efficiency. And it is in the field of efficiency that the engineer's greatest opportunities are limitless.

High-Frequency Heating of Conductors and Nonconductors

R. M. BAKER
MEMBER AIEE

C. J. MADSEN
MEMBER AIEE

TO heat electric conductors made of metals—iron, brass, aluminum, and so forth—the piece to be heated is surrounded by a coil carrying the high-frequency alternating current. This coil induces the heating currents in the work, and the process is called induction heating. The frequency used depends on the physical properties and dimensions of the piece to be heated.

To heat the so-called nonconducting materials such as wood and Micarta, the material is placed between high-voltage plates to form the dielectric of a capacitor. Heat generated in the material is dielectric loss, and the process is called dielectric heating. The frequency used depends principally on a measurable quantity called loss factor and the rate of heating desired. Whereas induction heating is inherently nonuniform heating, dielectric heating finds its greatest advantage in the fact that it gives almost perfectly uniform heating throughout a mass of material.

INDUCTION HEATING

Because this is a general discussion of induction-heating applications, the theory of induction heating will be presented in the simplest possible manner. The presentation will consist in the statement of a few facts, the proof of which can be found in any treatise on skin effect.

A typical arrangement for induction-heating a metal cylinder is shown in Figure 1A. In this representation, a coil of hollow copper tubing is close wound to form a helical coil around the piece to be heated (work piece). In order to reduce the coil voltage to a minimum and obtain good coupling to the work, the coil should conform as closely as mechanical and electrical considerations permit. Since high currents are used for induction heating, the coil is almost always water-cooled.

Alternating current flowing in the coil causes a countercurrent to flow in the work as indicated by the arrows of Figure 1A.

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R. M. Baker is section engineer, research laboratories and C. J. Madsen is electronic engineer, industry department, both with Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

If the frequency is high enough, the coil current will concentrate near the inside surface of the coil, and the work current will concentrate near the surface of the work piece. This effect generally is referred to as skin effect.

DEPTH OF CURRENT PENETRATION

In Figure 2 is shown a graph of the current density near the surface of the work. It is a maximum at the surface and dies off exponentially below the surface. Mathematical analysis shows that the total heating of the exponentially distributed current density is the same as would be produced by the same total integrated current flowing in a shell or layer (δ) inches thick, where δ can be calculated from the equation:

$$\delta = 3{,}170\sqrt{\frac{\rho}{\mu f}} \text{ inches} \qquad (1)$$

ρ = electrical resistivity (ohm-inches)*
f = frequency (cycles per second)
μ = magnetic permeability

This is called the depth of current penetration and becomes a useful concept in calculating induction-heating applications as will be shown later.

POWER GENERATED IN WORK

For the condition illustrated in Figure 1A (δ small in comparison to the diameter of the work piece) it can be shown that the total current flowing in the work is equal to the total ampere turns in the magnetizing coil. Thus if the coil carries 500 amperes and has ten turns, the current flowing around the periphery of the work piece will be 5,000 amperes. The heating can be calculated according to the last section by assuming that this total current flows in a layer (δ) inches thick. The resistance to the flow of this current is thus

$$R_w = \frac{p\rho}{\delta l_c} \text{ ohms} \qquad (2)$$

and the total power input is

$$I_w^2 R_w = (AT)_c^2 R_w \text{ watts} \qquad (3)$$

p = average length of current path (inches)
l_c = length of coil (inches)
$(AT)_c$ = rms ampere turns in coil

The density of heating can be obtained by dividing equation 3 by the surface area of the work piece under the coil. Thus,

$$\text{Watts per square inch} = (NI)^2 \frac{p\rho}{\delta p'} \qquad (4)$$

p' = outer perimeter of work piece (inches)
N = turns per inch in coil
I = rms amperes in coil

For the case shown in Figure 1A, p' is practically equal to p, but equation 4 is fairly accurate when δ is as great as one-third the diameter of the cylinder, and for this case p' will be considerably greater than p.

* Ohm-inches = ohm-cm/2.54.

If reference is made again to Figure 2, it is seen that a large part of the total current flows within a depth (δ) below the surface, and from the curve of relative heating (current density squared) it is seen that an even greater part (86.6 per cent) of the total heating occurs in this depth. Thus δ given by equation 1 not only is a convenient quantity for calculating power generated, but also gives a good indication of the depth of heating. The rate at which heat flows out of the region in which it is generated will be discussed later.

The convenience of equations 1, 3, and 4 lies in the fact that they may be used equally well to calculate the heating in other regular and irregular work pieces as indicated in Figure 1, B, C, and D.

To calculate approximately the power input to various metals equation 4 may be simplified by assuming $p' = p$. Thus,

$$\text{Watts per square inch} = (NI)^2 \frac{\rho}{\delta} \qquad (5)$$

or if the value of δ is substituted from equation 1,

$$\text{Watts per square inch} = 3.16 \times 10^{-4} (NI)^2 \sqrt{\mu f \rho} \qquad (6)$$

INTERPRETATION OF μ IN EQUATIONS

Metals like copper, brass, and aluminum, which commonly are called nonmagnetic have a magnetic permeability of unity, and to calculate heating or depth of current penetration in such a metal one simply substitutes $\mu = 1$ in the formulas.

For ferromagnetic metals like iron and nickel, experiments indicate that the value of μ to use is approximately 1.78 times the permeability at the surface taken from a magnetization curve for the particular value of ampere turns per inch used in the coil. For iron this value of μ is given for ampere turns per inch greater than 100 by the formula,

$$\mu = \frac{45{,}700}{NI} \qquad (7)$$

When the temperature of iron is above 780 degrees centigrade, it loses its ferromagnetic properties and becomes paramagnetic (commonly called nonmagnetic). When calculating heating or depth of penetration of current for this case, one simply substitutes $\mu = 1$ in the equations.

The theories of induction heating of metallic electric conductors and of dielectric heating of nonmetallic nonconductors are discussed in simple terms in this article for the benefit of those who are not specialists in this field. The various types of high-frequency heating, its applications to industry, and its advantages in economy, efficiency, speed, and adaptability are pointed out.

LIMITATIONS OF EQUATIONS

The simplified equations already given are strictly accurate only when the depth of current penetration calculated from equation 1 is small in comparison to the minimum dimension of the piece to be heated; however, they are sufficiently accurate for most work when the depth of current penetration is equal to or less than one-third the minimum dimension.

The equations for power input are strictly accurate only for coils long in comparison to their diameter or minimum dimension. For short coils, the power input per square inch will be less than indicated by the equations. Stated another way, the value of ampere turns calculated from the equations is the minimum value to give the desired power input and should be increased for short coils. A discussion of this effect will be found in several references listed at the end of this paper.

SPECIAL CURVES FOR IRON

A large percentage of induction-heating jobs involve heating iron or steel. Special curves giving power input per square inch at standard frequencies as a function of ampere turns per inch in the coil, for iron in the ferromagnetic condition (temperature below 780 degrees centigrade), Figure 3, and for iron with a permeability of unity (temperature above 780 degrees centigrade), Figure 4, are calculated from equation 6 and the average resistivity of iron in the respective temperature regions.

The depth of current penetration for iron below 780 degrees centigrade (ferromagnetic region) as a function of ampere-turns per inch in the coil is given by the curves of Figure 5.

The depth of current penetration in the paramagnetic region (above 780 degrees centigrade) is not dependent on magnetizing force, and is listed in Table I for convenient reference.

COIL LOSS

If the coil is close wound from copper strap or rectangular bar stock, most of the current will flow near the inside (next to work) surface of the turns. For good coil design, the radial depth of copper should be equal to or greater than the depth of penetration of current as indicated by equation 1. The distribution then will be identical with the curve of Figure 2, and the coil loss in watts per square inch of inside surface can be calculated from equation 6, using $\mu = 1$ and $\rho = 0.79 \times 10^{-6}$ ohm-inch. For convenience, this equation is plotted as curves in Figure 6.

The total coil loss will be given by the triple product of watts per square inch (from curve), inside perimeter of coil (inches), and length of coil (inches). If the turns are spaced, the copper loss for the same ampere turns per inch and same

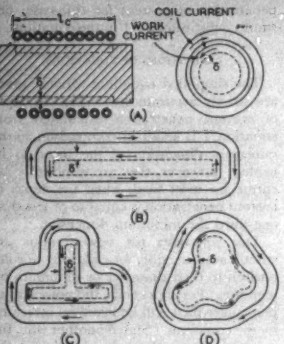

Figure 1. Induction heating of various shapes showing current paths

over-all length will be increased approximately in the ratio C_1/C_2 where

C_1 = pitch of turns (inches)
C_2 = axial width of conductor (inches)

The loss in a coil wound from hollow copper tubing will be about the same as for the strap-wound coil, provided the wall thickness of the tubing is greater than the depth of penetration of current.

For frequencies above 2,000 cycles per second, the coil usually is wound from hollow copper tubing so that it can be easily water-cooled. For lower frequencies, it is advantageous to use copper strap of suitable thickness with a copper tube soldered on the back of the turn for water cooling. One kilowatt per square inch is the upper limit of loss for easy water cooling in a multiturn coil. In the single-turn coil used in high-density heating, however, the kilowatts per square inch to be dissipated may be more than ten times this high.

CLASSIFICATION OF INDUCTION-HEATING APPLICATIONS

Induction-heating applications can be classified roughly in three groups according to the rate at which power is generated in the piece to be heated:

1. Low-density heating.
2. Medium-density heating.
3. High-density heating.

Typical of the first of these is the tin-brightening process which has so successfully used 200-kilocycle radio-frequency power to melt the thin tin surface on electrolytic tin plate. Although the process requires 1,200 kw of power with the strip running at 1,000 feet per minute, the surface density of power input is only about 240 watts per square inch of surface.

Typical of medium-density heating is the preferential hardening of large gears and the like where several kilowatts per square inch will be generated in the surface. The hardened case is generally of the order of one-eighth to one-quarter inch or more.

Table I. Depth of Current Penetration in Paramagnetic Region

Above 780 Degrees Centigrade

Frequency-Cycles Per Second	(δ) Inches
60	2.80
960	0.70
3,000	0.396
9,600	0.222
200,000	0.0485
450,000	0.0324

The very high-density heating is typified by the self-quenching technique which has been developed and publicized recently. In this process using megacycle frequencies and very high currents in a single-turn coil, power inputs of about 80 kw per square inch have been obtained.

The grouping indicated is obviously quite arbitrary, as other applications can be quoted requiring power inputs ranging from possibly ten watts per square inch to 100 kw per square inch. It is interesting, however, to note the range of requirements for different jobs.

RATE OF HEAT FLOW INTO WORK PIECE

It must be remembered that the heated region depends not only on the thinness of the shell in which the heat is generated but also on the rate at which heat flows into the heated piece. The general equations for heat flow cannot be given in the space available, but curves of temperature distribution in an iron slab for different times after one surface has been suddenly heated are shown in Figure 7.

In surface-hardening applications, it is necessary to heat the surface to hardening temperature and to have the temperature gradient at the surface steep enough, so that the metal a short distance below the surface is below hardening temperature. If the curves of Figure 7 are referred to, it will be agreed that hardening will occur to the depth where the temperature has dropped to 80 per cent of the surface temperature. The depth of hardening when heat is generated in an infinitely thin surface layer then will be represented by the equation:

$$h = 0.04\sqrt{t} \text{ inches} \qquad (8)$$

t = elapsed time (seconds)

In the high-density heating for self-quenching any point on the surface is subjected to heating for about 0.1 second. If we substitute in equation 8, this gives a depth of hardening of 0.0126 inch.

The rate of heat flow is also important when it is desired to heat a mass of metal uniformly throughout. The power input must be low enough to allow heat generated near the surface to flow into the body of the material. Induction heating always generates more heat near the surface than at the center of a piece. It is important when uniform heating is desired to choose a frequency as low as possible consistent with getting good coupling to the work (δ equation 1 not greater than one-third the minimum dimension).

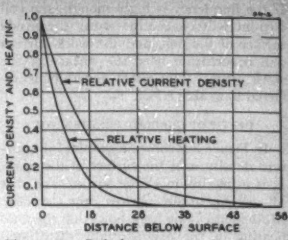

Figure 2. Relative current density and heating at various depths below the surface

$$\delta = 3{,}150\sqrt{\frac{\rho}{\mu f}} \text{ inches}$$

APPLYING HIGH-FREQUENCY INDUCTION HEATING

Induction heating is widely used in many industrial processes today. Many possible applications are still in the stage of development. Frequently a problem can be solved by the use of frequencies below 10,000 cycles. An example of this type might be the heating of steel ingots for rolling or forging. Others, such as thin case hardening, require frequencies in the millions of cycles per second.

In studying a particular problem, one of the first considerations is the amount of energy involved. A useful approximation can be obtained by the addition of the energy required to increase the temperature of the mass desired through the required temperature change, and radiation, convection, and conduction losses. The power required then can be determined by dividing this by the time involved. Neglecting radiation and conduction losses, the power can be readily obtained approximately from the equation:

$$W = K\frac{McT}{t'} \qquad (9)$$

where

M = pounds of material being heated
c = specific heat
K = constant 31.6 to give W in watts
0.0316 to give W in kilowatts
T = temperature change in degrees centigrade
t' = time in minutes

Where high temperature or high-temperature gradients are involved, radiation and conduction losses must be added to arrive at the total power required. The generator rating necessary for the application depends on this total power.

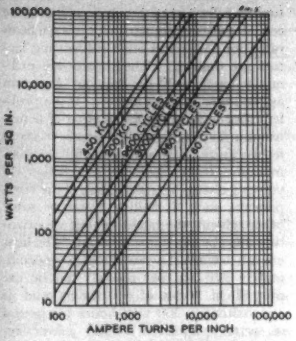

Figure 3. Induction-heating power input for iron below 780 degrees centigrade (ferromagnetic region)

$\rho = 15.7 \times 10^{-6}$ *ohm-inch*

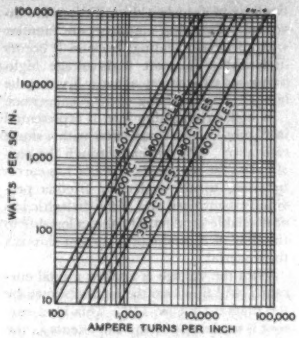

Figure 4. Induction-heating power input for iron above 780 degrees centigrade

$\rho = 47 \times 10^{-6}$ *ohm-inch*

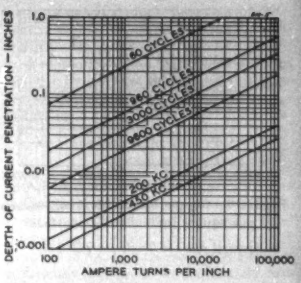

Figure 5. Depth of current penetration versus ampere turns for iron below 780 degrees centigrade (ferromagnetic region)

$\rho = 15.7 \times 10^{-6}$ *ohm-inch*

A quick estimate of the necessary generator rating may be obtained from the curves of Figure 8. These curves take into account material resistance, specific heat, and coil losses on average applications where a practical degree of coupling is obtained.

The choice of frequency, while not critical should be guided by a number of factors such as the size of the work in applications requiring complete heating or the depth of heating in surface heating cases. In the latter, the rate of heat flow into the material must be considered. The depth of the heating resulting from conduction is influenced by the time factor. Hence the power used may influence to a considerable degree the choice of frequency, or, conversely, a fixed frequency may be used for quite a variety of applications by controlling the amount of power supplied. The curves shown in Figure 9 give an indication of this phenomenon on a particular size shaft of one type of steel.

This agrees quite closely with the predictions of equation 8, although considerable deviation may be expected because of quenching technique. The material in curve 7 was water-quenched immediately after heating. The type quench and the grade of steel will influence to a considerable degree the results obtained in practice.

Coil design and construction have been covered by a number of articles and hence will not be considered here.

Occasionally problems are encountered where high concentrations of current are required in coils of one or two turns. Current transformers giving three to ten times the generator current in the secondary circuit are a practical means of obtaining higher currents in some applications of this type. Low secondary-circuit reactance is a factor which is extremely important if current ratios approaching the turns ratio are to be obtained.

Another method commonly employed to increase the coil current is the use of a capacitor in parallel with the work coil, to resonate the work circuit partially. This is an effective means of increasing coil currents up to about double the generator current.

APPLICATIONS OF INDUCTION HEATING IN INDUSTRY

Induction heating is being used today in many industries, in many types of processes. The following list of applications gives a fairly comprehensive view of the work which can be done, but it is not necessarily complete:

Annealing—metal tubing and sheet.
Bonding—clutch facings, cycle welding.
Brazing—tool tips and other products.
Chemical processes—catalysis, autoclave.
Heating for forging—bolt heads, rivets, and so forth.
Hot spinning—tube closure, and so forth.
Melting—metal alloys, tin.
Miscellaneous heating—drying painted surfaces.
Sintering—powdered metals.
Soldering—cans, bushings.
Spot annealing—die repairs.
Sterilization—surgical instruments.
Surface hardening—gears, shafts, tools, cylinders.
Through hardening—shells and tools.
Very thin surface hardening—thin-walled parts, tools, gears, bearings
Welding—pipe and other parts.

Figures 10, 11, and 12 illustrate three of the applications mentioned.

In general, it can be said that induction heating will be advantageous when more rapid heating than can be obtained by more conventional means is necessary or desirable. Such applications include surface-hardening processes or brazing operations which make it desirable to heat only the joint to be brazed without heating the whole piece. Soldering operations also will fall into this class, and induction heating is especially attractive because an entire seam can be quickly made and automatically timed by an inexperienced operator. The surface of an oil-well drill can be superficially melted to apply a layer of tungsten carbide or other wear-resisting material without deforming or damaging the body of the drill. A steel shaft moving through a coil can have its surface heated to such a shallow depth that self-quenching occurs as the heat soaks into the body of the shaft. Thin cylinder walls can be heated on the inside while the outside remains comparatively cool, thus producing a hardened inside surface with a tough shock-resisting wall. These are but a few of the important uses found for induction heating because of the high rate of heating possible by this method.

Another good general field of application for induction heating is in continuous processes. A good example of this has been the brightening of electrolytic tin plate traveling continuously through a coil at 1,000 feet per minute or fittings being soldered to small bushings as they are fed automatically into a turntable and through an induction-heating coil. Or special cans for capacitors can be soldered as they move past a coil on an endless belt. Iron wire can be annealed continuously at 1,000 feet per minute or more. One-inch steel rod can be heated continuously as it is fed into an automatic rivet-forging machine. Or aluminum slugs can be heated continuously as they slide down a chute to be forged. These applications require sizeable power inputs at moderate density.

Induction heating has found considerable use in the preheating or strain relieving of welded joints. Much of this work has been done at commercial frequency (60 cycles per second). It also has been used for such low-temperature applications as making shrink fits.

Induction heating has been considered for heating large drums used to roll cellulose fibers into wall boards and for the heating of reaction kettles. It even has been considered for thawing ore cars which freeze up in the winter so that they

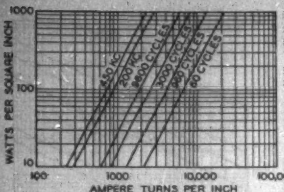

Figure 6. Copper loss in ideal coil—watts per square inch of inside surface

Curve of equation 6 with $\rho = 0.79 \times 10^{-6}$

can be satisfactorily dumped, and for heating steel ingots for rolling.

Most of the applications mentioned are very practical and economical. A few are technically possible, but the economics are questionable.

Heating of small rods (less than one-quarter inch in diameter) and thin sheet (less than one-quarter inch thick), except when these are of ferromagnetic material such as iron, steel, or nickel, is very difficult. Even these cannot be heated economically above the temperature at which they lose their ferromagnetism (780 degrees centigrade for iron) unless the finished product is especially valuable or cannot be heated by more conventional means.

DIELECTRIC HEATING

Dielectric heating is generally limited in application to those materials known as nonconductors of electricity. The piece to be heated is placed between two plates or electrodes to form a capacitor. A high voltage at high frequency (2–100 megacycles per second) is applied to the plates and heat is generated in the dielectric (material to be heated) by a kind of molecular friction brought about by the high alternating electric field. Since the field producing the stress is uniform throughout the thickness of a homogeneous material, the heating is ordinarily uniform throughout. This makes this type of heating particularly useful when thick sections are involved. Electrical engineers are familiar with dielectric heating, because it occurs undesirably in most high-voltage high-frequency capacitors; actually limiting the kilovolt-ampere rating of these capacitors.

A dielectric heating load is represented in Figure 13A by a capacitor with a shunt resistance. The current through the parallel resistor represents a power loss corresponding to the molecular friction previously mentioned and, if the dielectric has appreciable conductivity also, a loss due to the flow of a conduction current through the material.

With the voltage E applied a total current I_0 will flow into the load as shown by the diagram Figure 13B. This total current is made up of two components I_r, the inphase component and I_c, the purely reactive component. The power input will be

$$W = EI_r = 2\pi f C_0' E^2 \tan \delta \text{ (watts)} \qquad (10)$$

C_0 = capacitance of plates with air dielectric (farads)

ϵ' = dielectric constant of material to be heated

E = rms volts between plates

$\tan \delta$ = tangent of loss angle for material being heated (see Figure 13)

For small loss angles (low power-factor) $\tan \delta$ is approximately equal to $\cos \theta$, the power factor of the material.

Often the product $\epsilon' \tan \delta$ is combined in one constant ϵ'' called the loss factor of the material. When this substitution is made and C_0 is expressed in terms of plate area A (square inches) and plate separation d (inches), the power input to the work can be expressed by

$$W = \frac{1.41 A f \epsilon'' E^2 \times 10^{-12}}{d} \text{ watt} \qquad (11)$$

or

$$W' = 1.41 f \epsilon'' \left(\frac{E}{d}\right)^2 10^{-12} \frac{\text{watts}}{\text{cubic inch}} \qquad (12)$$

where E/d is the voltage gradient in the material being heated (volts per inch).

Equation 9 may be used for calculating the power required to heat a mass of material by the dielectric-heating means.

When this formula is applied to an actual high-frequency problem, it should be considered as an approximation, since heat-radiation losses and other influencing factors are omitted. These losses are ordinarily less than 20 per cent but in certain applications may be higher. If the problem simply involves the heating of a material a few hundred degrees above room temperature, it is a very useful approximation. If the temperature change involves a change in state of one of the components, such as boiling water or some other solvent, the latent heat of vaporization must be taken into account. The heat energy to convert water to steam (approximately 970 Btu per pound) can be expressed in terms of watt-hours and is approximately 300 watt-hours per pound of water vaporized. The power required can be expressed by

$$W = 300\ M' \text{ watts} \qquad (13)$$

where

M' = pounds of water vaporized per hour

In drying problems, this factor may be much greater than the power required to raise the temperature of the material at the desired rate and, hence, must be added to W obtained in equation 9 to indicate the total power required.

In designing leads and the coupling circuit, it is desirable to know the total current required by the load. This will be given by the equation:

$$I_0 = \sqrt{I_c^2 + I_r^2} \text{ amperes} \qquad (14)$$

where

$$I_c = 2\pi f C_0' E \text{ amperes} \qquad (15)$$

$$I_r = I_c \tan \delta \text{ amperes} \qquad (16)$$

FACTORS AFFECTING THE APPLICATION OF DIELECTRIC HEATING

In some applications, all factors in equation 11 or 12 except E and f are known and more or less fixed. In others A and d are subject to some variation by arrangement

Figure 7. Temperature distribution in an iron slab various times after surface temperature is established

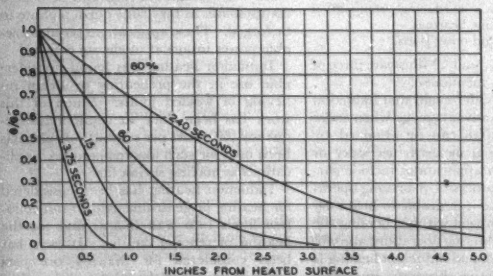

Figure 8. Generator rating versus pounds time degrees rise

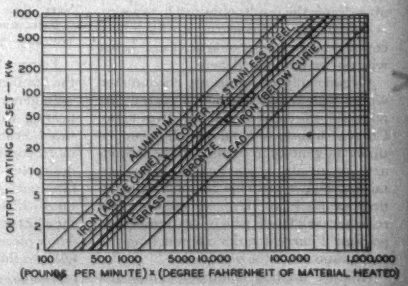

Table II. Approximate Loss Factor and Specific Heat of Several Common Materials

Frequency	Loss Factor ϵ'' 1 Mc	10 Mc	20 Mc	30 Mc	Specific Heat
Paperboard (soft)		0.024	0.026	0.027	
Paperboard (hard)		0.11	0.12	0.11	0.4
Fiber	0.25				
Porcelain	0.04	0.044	0.06		0.26
Oak dry	0.09				0.40
Birch dry	0.32				
Hard rubber	0.03	0.017	0.017		0.33
Plastics:					
Phenol formaldehyde	0.20 to 0.50				0.30
Urea formaldehyde	0.16 to 0.21				0.40
Cellulose acetate	0.03 to 0.45				0.35
Cellulose nitrate	0.43 to 0.62				

of material or variation of application electrodes.

The loss factor ϵ'' is a property of the material, and can be measured by means of proper equipment. Loss factor of a given material is quite likely to vary appreciably with frequency, temperature, moisture, and so forth; hence measurements must be made over a fair range of the expected variations in the process. A study of loss factor versus frequency sometimes discloses an optimum frequency for heating a particular material. Generally, however, this maximum is quite broad, extending over a range of five or ten megacycles. Table II gives the approximate loss factor and specific heat of a number of common materials.

FREQUENCY LIMITATION

The frequency chosen for a particular application is influenced by several factors, such as the area to be heated, electrode arrangement, practicability of oscillator or generator, design, and power. In order to keep the voltage within reasonable limits the frequency should be as high as practical. However, there are two factors that limit the increase in frequency, namely, voltage distribution and oscillator design.

For a given electrode size, the higher the frequency, the greater the probability of unequal voltage distribution over the area due to the standing-wave effect. Several methods of minimizing this effect are available but some precautions are necessary. If the longest dimension of the electrodes is a small fraction of a wave length, or if the work is scanned, this effect is minimized.

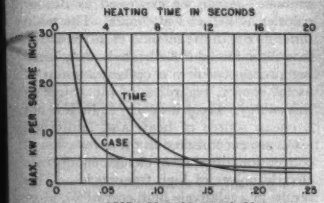

Figure 9. Depth of case versus time and power

Tool steel, 450 kilocycles

Ordinarily if the longest distance from the point of connection to the edge of the high voltage electrode is less than $^1/_{16}$ of a wave length, very little trouble will be experienced. The wave length on a load with a dielectric constant ϵ' is

$$\lambda = \frac{1{,}000}{f'\sqrt{\epsilon'}} \text{ feet} \qquad (17)$$

where

f' = frequency (megacycles)

The maximum frequency which can be used without trouble from standing waves (nonuniform heating) is therefore

$$f' = \frac{62.5}{l\sqrt{\epsilon'}} \text{ megacycles} \qquad (18)$$

l = maximum distance from point of connection to the edge of high-voltage electrode (feet)

Consider a load of plywood with a dielectric constant of 3. The maximum frequency for a load in which l is 5 feet, according to equation 18, will be

$$f' = \frac{62.5}{5 \times 1.73} = 7.2 \text{ megacycles}$$

The design of electronic generators for high power at high frequencies also presents difficulties.

From a practical viewpoint, at the moment it appears undesirable to use frequencies above 20 megacycles when powers above about 20 kw are involved. Fortunately, satisfactory performance in many applications is obtained with frequencies in the region of 2 to 15 megacycles. This range of frequencies is also satisfactory for the size of electrodes required for most applications.

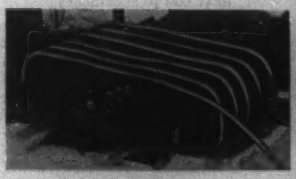

Figure 10. Removal of rubber from tank treads

The metal is heated by induction to a temperature which frees the bond between the rubber and the metal, thereby facilitating the removal of the rubber. Metal inserts in all types of rubber products can be heated easily by induction

VOLTAGE LIMITATION

From equation 12 it is seen that the power input to a material is proportional to the square of the voltage gradient (E/d). Even at relatively low frequencies (two megacycles) considerable power can be supplied to a load if the voltage gradient is sufficiently increased. Unfortunately, factors arise to limit the voltage which may be applied.

Ordinarily, the voltage across the work should be kept under 15,000 volts. It is not impossible to use voltages above this, but the additional precautions necessary to avoid corona and arc-overs are often more expensive than some other compromise of the engineering factors. The voltage gradient, that is, the voltage per inch permissible across the material, varies widely with the type of material. The radio-frequency voltage which will puncture a given dielectric material, is generally much lower than the 60-cycle voltage which a material will stand. Hence, it is desirable to keep the voltage gradient below 2,000 volts per inch on porous materials, and less than 5,000 volts per inch on the less porous materials, whenever possible.

Two methods are employed to reduce the hazard of voltage breakdown. The voltage may be reduced arbitrarily and the resultant slower heating accepted, or the frequency may be increased, and the factor E^2 reduced in proportion, thus maintaining the desired rate of heating. Frequency cannot be increased indiscriminately because of the frequency limitations discussed earlier. On the other hand, the work may be stacked so that several times

Figure 11. Brazing a metal fillet in a propeller section

Figure 12. Heating a rock bit in a controlled atmosphere to fuse particles of tungsten carbide into the cutting faces and edges

Complete process takes a little over two minutes

the original thickness is obtained, and the possibility of voltage rupture is thereby reduced or eliminated. For a given power input, the rate of heating per piece of work is reduced in proportion to the number of pieces stacked, but the total production will be increased in this same proportion so that the desired production can be obtained with less hazard.

Another type of voltage limitation may be reached in some applications where it is impossible to have the electrodes in contact with the work. This gives rise to a condition in which the space between the electrodes is occupied by two materials of widely different dielectric constants. See Figure 14. The potential distribution may be such in this case as to cause breakdown of the surrounding medium (usually air), resulting in burning of the material to be heated at the point where this failure occurs. The potential distribution may be conveniently calculated by means of the equation:

$$e_1 = \frac{E}{1 + \frac{\epsilon_1' d_2}{\epsilon_2' d_1}} \qquad (19)$$

where

e_1 = voltage across lower dielectric (material to be heated)
E = total voltage between electrodes
ϵ_1' = dielectric constant of lower dielectric (material to be heated)
ϵ_2' = dielectric constant of upper dielectric (air)
d_1 = thickness of lower dielectric (material to be heated)
d_2 = thickness of upper dielectric (air)

d_1 and d_2 can be expressed in centimeters or inches as long as both are in the same terms.

This should not be construed to mean that air gaps cannot be tolerated in dielectric-heating applications. It is perfectly satisfactory in some cases, when the air gap

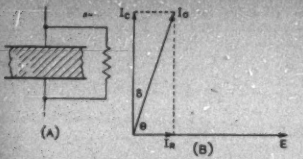

Figure 13. Dielectric heating—equivalent circuit and vector diagram

is not too large compared to the thickness of material to be heated, and the power involved is not too high. The loss factor of air is practically zero, so that little if any electric energy is lost in the air gap, but it does materially increase the voltage which must be applied to the electrodes and, hence, should be avoided if possible.

HEATING IRREGULAR SECTIONS

If the dimension d is uniform throughout the piece (assuming E is uniform and material is homogeneous), uniform heating throughout the area and volume of material between the electrodes is obtained. Note however that if d varies the heat generated per unit of time in any volume varies inversely with the square of the thickness, and uneven heating in the material will result, the thinner sections being heated more rapidly than the thicker sections. For this reason, it is desirable to have the work uniform in thickness and reasonably homogeneous.

There are methods which can be applied to assure uniform heating of certain types of nonuniform sections. If the work is of such a shape that two pieces of work can be placed in complementary positions and the resultant thickness be uniform, the material will heat evenly. For example, two wedge-shaped pieces may be placed together to form a rectangular cross section of uniform thickness. Also the electrodes may be spaced away from the material to be heated at its thinnest section, and be in contact with the material at its thickest point. This method is somewhat critical and if possible should be avoided in a production setup.

HEAT LOSS TO ELECTRODES

It may be found that material adjacent to the electrodes will not reach the desired temperature because of heat conduction to the electrodes. (No heat is generated in these electrodes by the dielectric-heating process.) This heat loss can be reduced by introducing a layer of heat-insulating material between the electrode and the material to be heated. This material will absorb some of the electric energy and, hence, must be included in a complete analysis. Another method would be to heat these outer electrodes by steam or other means to eliminate this heat loss. In this way, uniform heating can be obtained, and the process can be speeded up as well, since losses from the material will

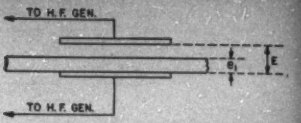

Figure 14. Dielectric heating with air gap

be offset by heat obtained from the heated electrodes.

APPLICATIONS OF DIELECTRIC HEATING IN INDUSTRY

Dielectric heating is particularly useful in heating materials of thick section, which may take several hours to heat by means of surface heating because of their limited thermal conductivity or to their thick section. Here the factors, economic as well as engineering, favor the application of dielectric heating.

The following list of applications in industry indicates the wide variety of processes in which dielectric heating is being used or is technically possible. Some of these are in the experimental stage to determine the economics of the application:

Annealing—rayon and nylon treating.
Bonding—plywood, plastics, shatterproof glass.
Chemical processes—catalysis and heating.
Cooking—food and meats.
Curing—rubber and plastics.
Drying—food, wood, ceramics.
Melting—fats.
Softening—plastic preforms and molding materials.
Spot heating—cementing and gluing of plastic and wood.
Sterilization—grain and package food products.

Dielectric heating is easily applied to the heating of articles moving continuously on a belt conveyor between high-voltage plates or electrodes, or between a high-voltage electrode and a grounded electrode. The articles thus may be heated for drying (driving off water), curing, or for numerous other uses.

ECONOMICS OF HIGH-FREQUENCY HEATING

The heat units produced by high-frequency technique are the same form of energy as obtained from conventional sources. It can be expressed as Btu or calories as well as watt-hours. The main difference is in the method of introduction into the material to be heated. Any heating process requires a certain amount of useful energy, regardless of the source of this energy. Electric energy in itself is not a cheap source of heat, and additional losses are encountered in the conversion of conventional-frequency electric energy into electric power of high frequencies. This results in a relatively high cost which must be offset by some advantage not obtainable by other methods. These advantages are enumerated later.

The high cost appears in two ways, first

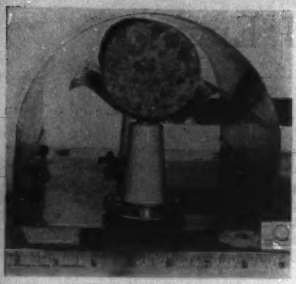

Figure 15. Dielectric heating of plastic preform for a particular molding operation

Reduced molding pressure, improved product quality, and increased production from a press make this application attractive

cost of equipment and cost of operation. To illustrate these factors, two curves are presented. Figure 16 shows the approximate first cost of high-frequency equipment of two types, rotating machine and electronic generators. Considerable spread is indicated for a particular rating because of the variation in accessory equipment such as voltage regulators, application electrodes or coil, necessary for various types of processes. On applications in which frequencies of less than 10,000 cycles can produce the desired rate or depth of heating, rotating machines are quite satisfactory. In fact, the economic picture at present is such that electronic generators are seldom applied at frequencies of less than 100,000 cycles. The cost of high-frequency energy (in terms of kilowatt-hours) as obtained from rotating machines is somewhat lower than that obtained from electronic generators as indicated by Figure 17. (These curves are based on electric energy at one cent per kilowatt-hour, amortization over ten years, average tube replacement, and maintenance.) These costs place electronic equipment at a disadvantage until technical limitations preclude the use of machine frequencies or other sources of heat. The limitations of these more conventional sources of heat, however, permits the use of high-frequency heating to advantage in a wide variety of applications.

High-frequency heating usually succeeds on one or several scores as indicated below:

1. It produces a result not possible by other methods of heating.

2. It increases the speed of a process and saves labor cost.

3. It produces or confines the heating to the part or point where needed, thus reducing the over-all power consumption.

4. It is clean and compact.

5. It reduces rejects, or improves the production quality of a product.

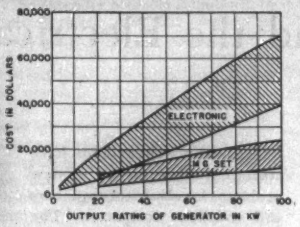

Figure 16. Approximate high-frequency generator costs (including accessories)

6. It is flexible in its application to a variety of operations or processes.

These advantages are often of sufficient importance to make the over-all economics attractive.

SUMMARY

Induction and dielectric heating provides industry with a useful tool. It can produce results not readily achieved by conventional heat sources and has its widest application (because of economics) to problems of this type. It is used successfully in industry today for brazing, soldering, melting, bonding, heat treating, case hardening, curing and many others. The materials involved include iron, steel, brass, copper, plastics, wood, paper, nylon, rayon and other synthetics, rubber, foods, and so forth. New developments will broaden the field and improve the technique of high-frequency heating, but sound judgment and careful study must be employed to assure an economically successful application.

SYMBOL NOMENCLATURE

Although symbols are defined in the text when first used, they are listed as follows for convenient reference.

A = area of material between electrodes (square inches)
$(AT)_c$ = total rms ampere turns in coil
C_0 = capacitance with air dielectric (farads)
C_1 = pitch of coil turns (inches)
C_2 = axial width of coil conductor (inches)
c = specific heat
d = plate separation, thickness of dielectric material heated (inches)
d_1, d_2 = see equation 19
E = voltage across dielectric load (rms volts)
e_1 = voltage across lower dielectric rms (see equation 19)
f = frequency (cycles per second)
f' = frequency (megacycles per second)
h = approximate depth of hardening (inches)
I = coil current (rms ampere)
I_c = out-of-phase current in dielectric heating
I_r = inphase current in dielectric heating
I_0 = total current in dielectric heating
I_w = current in material heated inductively

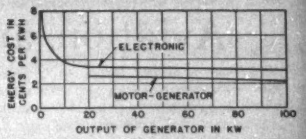

Figure 17. Approximate cost of high-frequency energy (including tube replacement, maintenance, amortization, and power)

K = constant (see equation 9)
l = see equation 18
l_c = axial length of coil (inches)
M = pounds of material heated
N = turns per inch in coil
p = average length of current path (inches)
p' = outer periphery of work (inches)
R_w = resistance of the work (ohms)
T = temperature rise (degrees centigrade)
t = time (seconds)
t' = time (minutes)
W = total power input (watts or kilowatts)
ϵ' = dielectric constant
ϵ_1', ϵ_2' = see equation 19
$\epsilon'' = \epsilon' \tan \delta$ = loss factor
δ = effective depth of current penetration (inches)
λ = wave length (feet)
$\tan \delta$ = tangent of loss angle in dielectric heating
ρ = electrical resistivity (ohm-inches) (ohm-inches = ohm-cms/2.54)

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Aviation and the Electrical Engineer

T. B. HOLLIDAY
MEMBER AIEE

Rapid advances in aviation have created a whole series of new problems for electrical engineers and aviation designers. The electrical and aviation industries must work together to develop satisfactory aircraft electric equipment, standardize minimum requirements for such equipment, and educate members of both industries to comply with these standards.

EVERYONE is familiar with widely publicized advertising in recent periodicals which states that an airplane can go from the local airport to any other airport in the world in 60 hours. For many this is dramatic notification of the possibilities in aviation.

Engineers who work with aviation are brought face to face with a whole series of new problems as a result of this ability to reach any place in 2½ days. At the same time these engineers must accept a new and more comprehensive responsibility. Designing equipment for an airplane is not like designing equipment for industry, the automobile, or the household. Further, the operator of an airplane cannot afford to have a device quit in flight, as results may be disastrous.

WEIGHT A PROBLEM IN AIRPLANE

One of these problems is weight. A pound saved in a commercial transport airplane is worth its weight in gold. In a military airplane each pound saved means that three additional rounds of 50-caliber ammunition can be carried. Any one of these three rounds might make the difference between a safe return to base and no return at all. The aviation engineer considers anything and everything as being too heavy. He is continually striving to eliminate ounces—which in turn mean pounds—from the completed airplane.

The electrical engineer too often is unconcerned about weight, since he is several steps away from the aircraft designer who has primary responsibility for weight.

Weight is so important to the aviation designer that he will sacrifice efficiency and some measure of reliability to attain a minimum weight. This is contrary to the tenets of the electrical engineer who is skilled in the more conventional lines of electrical design.

The performance of the airplane depends on weight. The ability of the airplane to clear the field on take-off; its ability to climb; its high speed, range, and service ceiling; and its landing speed are all dependent on weight. It is little wonder that the aeronautical engineer consistently endeavors to eliminate every unnecessary ounce.

The normal fighter airplane can be divided into weight groups as follows:

Aircraft structure	40 per cent
Equipment	40 per cent
Pay load	20 per cent

Every fraction of weight that can be eliminated from the 40 per cent equipment can be added to the 20 per cent for pay load. In the fighter airplane this means more gasoline and consequently more range, or it means more ammunition and therefore more fire power. M. Boe, in an article for *Aero Digest* which was subsequently reproduced in a British magazine, *Flight*, has stated that the weight of instruments and small accessories produced by the Germans was 10 to 15 per cent lighter than their corresponding American counterpart. This apparently small difference in the weight of each accessory provides for a great deal of gasoline or armament.

SUPPORTING STRUCTURE A FACTOR

Another factor which cannot be neglected is that each pound of equipment which is added to the air frame requires approximately one-half pound of structure to mount and support that piece of equipment. If eight per cent can be saved in the weight of equipment, a fighter airplane having a gross weight of 7,250 pounds can increase its range by 25 per cent, or it can increase its fire power by 750 rounds of 50-caliber ammunition, or 17 square feet of armor plate can be added. The eight per cent saving may be the means of bringing its own airplane home or of protecting a bomber for a longer range. According to Mr. Boe, a weight reduction of 3½ per cent in the total airplane would increase the ceiling by 3,000 feet. All of these ounces which are saved in individual items of equipment can add up to a sufficient margin to be the margin of victory.

It is inevitable that these efforts to decrease weight will result in an increase in cost. However, it must be remembered that military airplanes cost five to ten dollars per pound, that commercial transports cost three to four dollars per pound, and that sport airplanes cost two to three dollars per pound. There are special instances of much higher prices. It is plainly evident that a different sort of thinking is needed for this type of vehicle as compared to the automobile which costs 30 cents per pound.

INCREASE IN COST JUSTIFIED

A higher cost is justified, because the return on the investment is correspondingly higher. A pound has a potential value of more than $200 per year to the air lines, but as yet the useful life of an airplane is not known. Most transport airplanes in use today are more than five years old, indicating that the pounds saved have a potential value of $1,000. In the military airplane a pound represents three to four rounds of 50-caliber ammunition. Any one of those rounds may be the one which makes it possible for the airplane to return home safely.

The relation of weight to airplane performance can be described by the following information:

(*a*). Maximum speed ..... $V_m \alpha \sqrt{W}$

(*b*). Landing speed ..... $V_s \alpha \sqrt{W}$

(*c*). Rate of climb ..... $V_c \alpha 1/W$

(*d*). Service ceiling ..... $A \alpha 1/W$

(*e*). Range of the airplane ..... $L \alpha \frac{W}{W \text{ empty}}$

As the size of airplane increases, the amount of fuel which must be carried increases in proportion. It is in these types of aircraft that the efficiency of equipment items becomes important. An engine will consume 0.4 to 0.5 pound of fuel per horsepower per hour of operation. The better generators which are mounted on this engine have an efficiency of 70 to 80 per cent at their usual load. The loss of power in the wiring is limited to approximately three per cent. Motors will have an efficiency of 50 to 80 per cent, depending on size and design.

If one takes as an example an over-all efficiency of 50 per cent for a motor and its generator, a one-horsepower motor will be responsible for a fuel consumption of one pound per hour. Operating at reasonable speeds, this motor may have a fixed weight of eight pounds. The maximum range of DC-3 transports now used on commercial air lines is about eight hours. In such an airplane, the motor which weighs eight pounds would consume eight pounds of fuel making a total weight of 16 pounds. It is possible to build airplanes having a range much higher than eight hours, and in fact such are already in use for trans-

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T. B. Holliday is colonel, air technical service command, United States Army Air Forces, Dayton, Ohio.

oceanic service. If the range is 20 hours, then the fuel consumed by the motor is 20 pounds, and this is much higher than the fixed weight of eight pounds. If by increasing the fixed weight of the motor to 8.5 pounds the weight of fuel consumed can be reduced to 18 pounds, a worthwhile saving has been made.

This type of argument does not apply to intermittently operated motors. In this type of motor it is desirable to strive for the minimum fixed weight at a sacrifice in efficiency. A motor which is used for only a few seconds in a long flight must have a minimum of weight. The worst example of this sort is the engine starter. This motor is used for only a few seconds, and more important it is used only on the ground. This type of equipment should weigh as close to 0 pounds as the designer can make it.

Similarly, space is an important problem. Most aircraft devices are too big to suit the aerodynamicist. Large devices require much space, and this means a bigger fuselage or a thicker wing. In either event the power required is increased, and the performance of the airplane is reduced. Perhaps it is fortunate that most accessory manufacturers will find themselves faced with the problem of designing a piece of equipment to fit in the available space. This means that the designers of the engine and structure have the first opportunity to restrict space, and, while the result may be arbitrary, the accessory manufacturer must live with that decision.

RELIABILITY ESSENTIAL IN AIRCRAFT

A problem which faces every designer is that of reliability. Reliability is essential in aircraft. While a satisfactory life of equipment without attention is much shorter for aircraft devices than it is for industrial devices, it is still a serious design problem. If an electrical device can be depended upon for continuous operation for more than 1,000 hours without any attention and for a life of 5,000 hours with some attention, it normally will be satisfactory. Every effort must be made to avoid nuisance failures, as these can alter transport schedules and can cause an aborted mission in military aircraft. For example, pilots of air-line transports habitually check their landing lights prior to take-off. If a lamp fails during this check, the airplane must be brought back to the hangar and relamped.

Half the problem of obtaining reliability is answered by proper system protection. Continuity of service is just as important to the aircraft electric system as it is to the public utility. In fact, a multigenerator installation in aircraft has many of the same problems as a multistation network.

Protection can be divided in four parts:

1. Generator-relay backup protection.
2. Bus and feeder network protection.
3. Circuit protection.
4. Equipment protection.

The generator normally is protected by a reverse-current relay, but a backup device is needed for the rare instances when a relay may weld. This is important in a dual-generator installation, since the entire output of one generator can be absorbed through a defective relay if the other generator is out of action. The backup device should be polarized to pass any amount of current in a forward direction, and it should have such current–time characteristics that it does not function until the reverse-current relay has had every opportunity to operate.

Bus and feeder networks should be so designed that accidental grounds and combat damage will interfere with a minimum section of the supply network. While open wiring has exceptional facility for clearing itself of damage, no efforts should be spared to make the system even better. Channeled feeder circuits with sectionalizing protective devices represent the ultimate in network protection.

The device which protects circuits should protect only the wiring and not the equipment load. This may be a fuse or circuit breaker, although the latter has a tremendous advantage when the supply problem is being considered. Since the device protects wiring, its current–time response should be proportional to those characteristics of conductors in the worst ambient temperature.

INTEGRAL PROTECTION IMPORTANT

Equipment must be protected integrally. For example a radio receiver using smaller conductors within than that of the power-supply line should be internally protected by a fuse, circuit breaker, or other device. Motors are the weakest link in the electric system. They fail quickly under overload or stalled operation. They must have integral protection against burn-out with the resultant problem of replacement.

The second half of providing reliability is to design equipment so that it can be operated in any environment.

These operating conditions under which an airplane must function bring a whole set of new problems. There are eight of these as follows:

1. Altitude.
2. High temperature.
3. Low temperature.
4. Vibration.
5. Sand.
6. Salt.
7. Humidity.
8. Radio noise.

Aircraft designers are dreaming of the day when airplanes will be able to fly at altitudes of nine or ten miles. This means that electric-equipment manufacturers must anticipate this probable operating condition. It is well known that the atmosphere is very cold at such altitudes, but not withstanding this fact it is difficult to cool electric apparatus properly. This is due to the fact that the density of the air decreases faster than the temperature. At 18,000 feet the air is one-half sea-level density; at 36,000 feet it is one-fourth. At the same time the low temperature combined with low density removes practically all the moisture from the atmosphere. Because of the increased activity of gamma ions and other causes, the ionization potential is a small fraction of its sea-level value, and this increases the likelihood of insulation breakdown. The problem of insulating electric circuits at these high altitudes is approximately four times as severe as it is at sea level. It is essential that electric apparatus be designed for excellent commutation as arcing cannot be tolerated. Arcing which might be considered minor at sea level can become a continuous flame at high altitudes.

OPERATION AT EXTREME TEMPERATURE

It is unwise to ignore high temperatures. While the temperatures within the temperate zone of the continental United States are quite reasonable, it must be remembered that an airplane can be at the hottest place in the world within 60 hours. This leaves no opportunity for changing of the equipment to accommodate the coming atmospheric conditions. For this reason, it is common practice to design equipment to withstand operating temperatures of plus 165 degrees Fahrenheit. This is based on ambient temperature of approximately 130 degrees Fahrenheit with some addition for the increase of temperature within the airplane due to accumulated heat.

The aforementioned temperature can occur on the ground. It is common practice to operate the engine compartment at 140 degrees Fahrenheit at all altitudes. This high operating temperature combined with the low density of the atmosphere already mentioned makes a still more difficult cooling problem. It is quite likely that this operating temperature will increase to still higher levels such as 250 degrees Fahrenheit.

At the other extreme, minus 65 degrees Fahrenheit often can be encountered on the ground in the arctic regions. This is the common design requirement for ground operation. However, it is known that at high altitudes above the tropic zones temperatures as low as minus 110 degrees Fahrenheit can be encountered. At first glance this would not seem to be serious, since the equipment normally will be operating and will be warm. However, spare equipment often is called upon for service at these temperatures and must be able to function. Likewise, if a rapid descent is made from such altitudes, many pieces of equipment which normally are used for landing will be called upon to function before they are warmed to operating temperature.

For many years a vibration-frequency range of 10 to 55 cycles per second has

been the standard test for aircraft equipment. This is inadequate. Many failures of engine-driven accessories have occurred at vibration frequencies of nearly 200 cycles per second. Harmonic frequencies to 500 cycles per second can be expected. The electrical designer must assume that the product is going to be operated at the critical frequency and must function satisfactorily and continuously when so operated.

Sand and dirt have caused more failures of electric apparatus by clogging relays, magnetic contactors, and bearings than any one would guess. For this reason it is now common practice to require that all relays be sealed against sand, dirt, and atmosphere. This sealing of the relays eliminates not only sand and dirt but also moisture and salt. It permits satisfactory operation at altitude, and it may permit an increase in the rating of a given size.

Atmosphere containing salt eventually will cause any poorly designed piece of electric apparatus to fail. When the airplane is operated in tropical climates, this salt will work its way into all parts of the apparatus and will cause a short circuit across the surface of insulation. In addition, it hastens the corrosion of exposed parts. The Navy Department has faced this problem for many years, and many of their practices have been lifted bodily by the aviation industry to combat this problem.

Humidity alone will cause early failure of any type of electric apparatus unless proper precautions are taken. These failures are due to rust and corrosion in metal parts and to fungus growth in cloth and leather goods.

Tests of humidity alone concern only moisture. Electric equipment also should withstand leakage of lubricating and hydraulic oils, gasoline, cleaning fluids, and other chemical agents used by the aeronautical industry.

ELIMINATE RADIO NOISE

Most electrical engineers realize that the current war is a radio war. This means that electric apparatus must not cause interference with the proper performance of radio equipment. The electrical engineer must assume this responsibility at the outset and make proper precautions in the original design so that unnecessary radio noise is not propagated through space or along the conductors.

In conclusion, while it can be stated that the problems facing the average electrical engineer are difficult, it also can be said that he must meet these problems. The electrical industry cannot ask the aviation industry to use electric equipment unless that equipment equals all other types in all respects and excels it in some. Accordingly, the problem in general includes not only the development of satisfactory equipment, but also the conduction of a program to educate aeronautical engineers in the proper application of this equipment. It is essential that professional and industrial groups work together on this program. An immediate task is suggested as follows:

1. Determine operating conditions.
2. Standardize minimum requirements for aircraft electric equipment.
3. Define adequate tests for insuring compliance with these standards.
4. Educate industry members or otherwise enforce compliance with these standards.

Rectifiers and Inductive Co-ordination

D. J. McDONALD
ASSOCIATE AIEE

NOISE induced from power-supply circuits into circuits used for transmission of speech or music is caused by the harmonic-frequency voltages and currents present in the power-system wave shape.[1] The interfering effect of a foreign voltage on a telephone circuit depends on its frequency, increasing with frequency up to a certain value and then decreasing. The voltage induced in a telephone circuit by a given voltage or current on a power-supply circuit also depends on the frequency, the mutual relation or coupling being directly proportional to frequency. When the effect of harmonics present on the power circuits is considered, it is necessary to give due weight to both factors. The term "inductive influence" is used in discussing them. The inductive influence of a power-system voltage or current wave shape is measured in terms of "telephone influence factor,"[2] abbreviated "TIF", which factor takes into account the variation of both the interfering effect and coupling with frequency. Figure 1 shows two TIF curves, one designated 1935 and the other tentative 1941.[3] The shape of the curve depends, of necessity, on the characteristics of the telephone instruments in use, and the change from the 1935 to the 1941 curve reflects the improvements that have been made in telephone instruments. The 1941 curve is just coming into use now, and the majority of the investigations made in recent years have been based on the 1935 curve.

The co-ordination problem introduced by mercury-arc rectifiers appears on both the d-c and the a-c circuits connected to them. The d-c problem was the first one to be encountered. Incidentally, one of the early rectifier problems was encountered in Montreal, and the control measures applied on that installation still are generally used. This article, which discusses effects on both the d-c and a-c systems, applies specifically to polyphase rectifiers of the common mercury-cathode type. It also applies in general to single-anode rectifiers of the mercury-cathode type operating in either glass bulbs or metal tanks.

EFFECTS ON D-C SYSTEMS

The common-cathode mercury-arc rectifier is usually built with 6 or 12 phases. Figure 2A is a schematic diagram of one of the common methods of operating a six-phase rectifier. Figure 2B shows the wave shape of the direct voltage at no load, and Figure 2C shows it under load. The voltage consists of a d-c component with a superimposed ripple. The ripple can be analyzed into a series of harmonic frequencies. Table I shows the harmonic voltages for a 60-cycle system expressed as percentages of the average direct voltage.[4] Only a limited number of measurements under load are represented, and values outside this range may be expected.

With a higher number of phases the harmonic frequencies are correspondingly higher; for example, in an ideal 12-phase installation the harmonic frequencies are 720 cycles and its multiples. In practice it is found that all the harmonics present with a six-phase group are present also with a higher number of phases, but those of 360 cycles, 1,080 cycles, and so forth, are reduced in magnitude, the reduction depending on the characteristics of the installation.

Filtering has proved to be the most gen-

D. J. McDonald is foreign wire relations engineer, Bell Telephone Company of Canada, Ltd., Montreal, Quebec, Canada.

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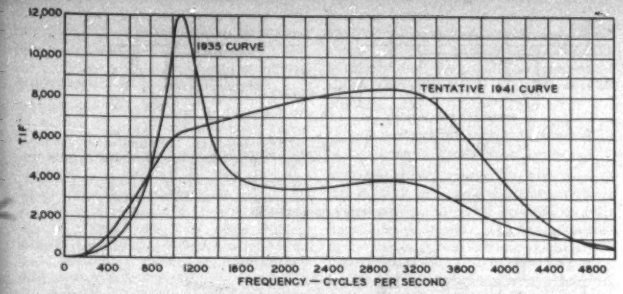

Figure 1. Comparison between TIF weighting curve adopted in 1935 and curve adopted tentatively in 1941, reflecting the improvements made in telephone instruments

The tentative 1941 weighting curve is based on FIA line weighting as given in engineering report 45 of the Joint Subcommittee on Development and Research of the Edison Electric Institute and Bell Telephone System. Scale based on 1,000-cycle TIF of 6,000

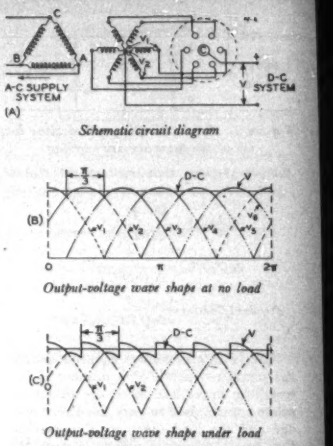

Figure 2. Schematic diagram and output-voltage wave shapes of six-phase mercury-arc rectifier

erally satisfactory method of controlling the harmonics impressed on the d-c system.[4] Figure 3 is a schematic diagram showing a common arrangement of the equipment. It consists of an inductive reactor in series with the circuit and a number of tuned shunts connected across the system on the load side of the reactor. A tuned shunt is required for each of the harmonics that is to be suppressed. The usual experience is that if shunts are provided for three or four frequencies, they will also reduce to some extent all the higher-frequency harmonics present. The design of the filtering equipment depends of course on the characteristics of the particular case. It is generally quite practicable to make the equipment such that the voltage TIF on the d-c system is comparable to the values found on systems supplied by rotating machines.

The problem of co-ordination with the d-c system arises usually only where rectifiers are used to supply traction circuits, either street railways or other electrified railways. In most other cases the d-c circuits are confined to the immediate vicinity of the load and are short, and it is possible to avoid communication-circuit exposures to them.

EFFECTS ON A-C SYSTEMS

It is a characteristic of a mercury-arc rectifier that harmonics are present in the load current taken from the a-c circuit even though they are not present in the generated voltage applied to the supply system.[5,6,7] To assist in obtaining some idea of what happens, consider an ideal case in which the alternating voltage is a pure sine wave and the impedance of the a-c supply circuit and of the rectifier transformer are negligibly low. In Figure 4A the wave form I_A shows the current in one phase of the three-phase circuit supplying a six-phase rectifier.[3] Wave form I_B is the same quantity for a six-phase rectifier with a different connection of the primary windings of the rectifier transformer. One primary connection is star and the other delta. The wave shapes depart markedly from a sine wave.

Analysis of the wave shape of I_A or I_B shows that it consists of a series of harmonics represented by $ps \pm 1$ where p is the number of phases and s is any whole number.[3] For a six-phase rectifier the frequencies are the odd nontriple harmonics, and for a 60-cycle system they are 300 and 420 cycles, 660 and 780, 1,020 and 1,140, and so forth. In the theoretical square wave the magnitude of the nth harmonic is $1/n$ times the magnitude of the fundamental-frequency current. The currents are identical in each phase of the three-phase supply circuit so the harmonics introduced are balanced components.

The distortion of the voltage wave shape depends on the impedance at harmonic frequencies looking back into the power system. A simplified view of what occurs may be obtained by considering the rectifier as a generator of high internal impedance which feeds back into the power-supply system. Figure 5 is a schematic diagram which demonstrates the action.[6] The harmonic voltage E_n produced by the rectifier acts on a circuit consisting of the internal resistance of the rectifier R_0 in series with Z_{ss}, the impedance of the rectifier transformer, and Z_{ss}, the impedance looking back into the supply system. Since the rectifier load is a balanced three-phase load and the effects are alike for each phase, the diagram shows the circuit for only one phase to neutral.

The increasing use of large mercury-arc rectifiers during recent years has introduced new inductive co-ordination problems between electric power-supply and communication lines, and the probable expansion in the use of this equipment in the postwar years is expected to intensify these problems. The subject has been treated at length in previous technical papers and publications, some of which are listed in the references; this article reviews the over-all problem and discusses its more important aspects.

Examination of the diagram helps in understanding the following conclusions that have been reached as a result of measurements on rectifier installations:

1. The harmonic currents increase with increasing load on the rectifiers. This corresponds to a reduction of R_0, the rectifier internal resistance, as the load increases.

2. For a particular rectifier, the harmonic currents depend on the total impedance in the circuit, namely, on the rectifier load and the impedances of the rectifier transformer and of the supply system.

3. The harmonic voltages appearing on the supply system depend on the harmonic currents flowing and also on the system impedance Z_{ss}. The voltage is directly proportional to Z_{ss} for a particular value of current. Any arrangement of the power system that reduces the impedance looking back into it from the rectifier will usually reduce the voltage-wave-shape distortion. Conversely, an increase in the system impedance will increase the effects.

4. The larger the rating of the rectifier, the lower will be its internal resistance and the impedances of the rectifier transformer and supply system. Hence the harmonic currents increase with the load rating of the rectifier.

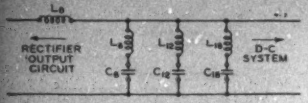

Figure 3. Schematic diagram of filter for six-phase mercury-arc rectifier

Relations between shunt constants for 60-cycle supply system:

$$2\pi(360)L_6 = \frac{1}{2\pi(360)C_6}$$

$$2\pi(720)L_{12} = \frac{1}{2\pi(720)C_{12}}$$

$$2\pi(1{,}080)L_{18} = \frac{1}{2\pi(1{,}080)C_{18}}$$

The harmonic voltage E_n produced by the rectifier depends on a number of factors. An important one is the amount of phase control used to vary the direct voltage and the load taken by the rectifier. For small values of phase control the change is not great, but for values beyond a few per cent the harmonic currents increase rapidly with increasing phase control. There is also evidence that the wave-shape distortion depends on the nature of the d-c load supplied by the rectifier.

MULTIPHASE OPERATION[8,9]

In the early investigations of the effects of rectifiers on a-c power-system wave shape, it was found that the distortion was less for 12-phase operation than for six-phase. Figure 4A shows two six-phase rectifiers arranged for 12-phase operation by using a star-connected primary for one of the rectifier transformers and a delta-connected primary for the other.[8] As mentioned previously, wave forms I_A and I_B show the wave shape of the currents in one phase of the three-phase circuit supplying each six-phase rectifier. Wave form I_C shows the wave shape of the current to the 12-phase group (vector sum of I_A and I_B), which approaches a sine wave more closely than either I_A or I_B.

In a polyphase rectifier each anode fires once during each cycle of the applied voltage. The anodes are arranged symmetrically so that the time intervals between the firing of successive anodes are equal. For a rectifier with p phases, the phase interval between anodes which fire successively is $360/p$ degrees.

In a six-phase rectifier the phase interval between the firing of successive anodes is 60 degrees and in a 12-phase rectifier it is 30 degrees. If a number of six-phase units are associated in such a manner that the phase interval between the firing of successive anodes is decreased, it is equivalent to increasing the number of phases. For example, 15 degrees between successive anodes corresponds to 24-phase operation, 12 degrees to 30-phase operation, 10 degrees to 36-phase operation, and so on.

For ideal conditions the harmonics produced in the a-c system would be the series $ps \pm 1$ where p is the equivalent number of phases and s is any whole number. For 30-phase operation the lowest harmonics would be the 29th and 31st, corresponding to frequencies of 1,740 and 1,860 cycles on a 60-cycle system. Table II shows for such theoretical conditions the harmonics that would be present on a 60-cycle system for different numbers of recifier phases.[9] On a 25-cycle system the harmonics and the percentages would be the same but the frequencies would be lower in proportion to the fundamental frequency. In practice the harmonics that are shown as suppressed are only partially suppressed, the amount depending on the characteristics of the installation and the manner in which the rectifiers are operated.

A number of methods may be used for obtaining multiphase operation. In general the individual rectifiers, if multianode, or groups of rectifiers if single-anode units are used, are six-phase. Two common methods of obtaining 12-phase operation are shown in Figure 4.[9] Figure 4A shows the use of star and delta primary connections on the rectifier transformers to obtain 30-degree phase displacement. Figure 4B shows the use of two sets of six-phase zigzag secondary windings on the rectifier transformer. The zigzag connection provides a 15-degree phase displacement; one set of windings is connected to advance the anode voltages 15 degrees while the other set retards 15 degrees, thereby providing a 30-degree displacement between the two sets.

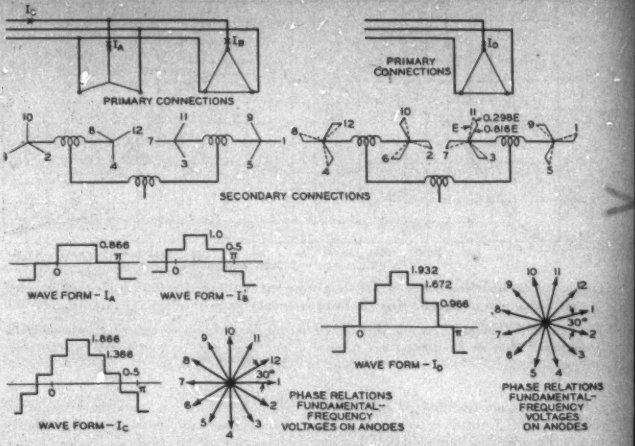

Figure 4. Schematic diagrams and wave forms for two 12-phase rectifier arrangements

A (left). Primary windings of rectifier transformer connected wye, delta; secondary, quadruple wye
B (right). Primary windings of rectifier transformer connected delta; secondary, quadruple zigzag

Phase displacement in three-phase circuits may be made readily by means of phase-shifting transformers as shown schematically in Figure 6.[8,9] The vector diagram indicates how the secondary voltages are shifted with respect to the primary voltages. The transformer can be designed to provide phase shift of any value up to 120 degrees. By interchanging the supply and load connections, the phase shift can be made either plus or minus.

Figure 7 shows two methods of using phase-shifting transformers to obtain 36-phase operation with six six-phase units.[9] The first method employs phase-shifting transformers to do all the phase-shifting. All the rectifier transformers are alike. It may be noted that as much as +25 degrees is required in one phase-shifting transformer and −25 degrees in another. The second method employs phase-shifting transformers in association with delta and star primary connections on the rectifier transformers. In this way it is possible to limit to 10 degrees the maximum shift to be provided by phase-shifting transformers.

It was stated hereinbefore that the har-

Table I. Harmonic Voltages in D-C Output of Six-Phase 60-Cycle Rectifier

Order of Harmonic	Frequency of Harmonic (Cycles Per Second)	Percentage Ratio of Effective Harmonic Voltage to Average Direct Voltage	
		No Load (Theoretical)	Measured Under Load
6	360	4.04	4.5 –5.95
12	720	0.98	1.26–1.37
18	1,080	0.44	0.53–0.90
24	1,440	0.25	0.61–0.72
30	1,800	0.16	0.40–0.80
36	2,160	0.11	0.43–0.62
42	2,520	0.08	0.41–0.44
48	2,880	0.06	0.35–0.36

monics which are shown as suppressed with ideal multiphase operation are only partially suppressed in an actual case. To obtain maximum suppression, the following requirements should be observed:

1. All units comprising the multiphase group should be identical and should carry the same load. If phase control is used, it should be substantially the same for all units.

2. The impedance of the rectifier transformer plus that of the phase-shifting transformers, if used, should be identical for each six- or 12-phase unit. If phase shifting transformers are not needed for some of the units, inductive reactors of equal impedance may need to be substituted.

3. The phase-shifting transformers or other devices used should provide exactly the phase displacement required. Even a small departure at the fundamental frequency will be large when referred to the higher harmonic frequencies.

In some installations suppression ratios as high as 80 to 1 have been obtained for the harmonics below about the 19th. For the higher frequencies it is not possible to do so well, ratios of the order of 5 to 1 being more common.

If one or more six-phase units of a multiphase group are shut down, balanced multiphase operation no longer is obtained. The magnitude of the effects on power-system wave shape may be deduced by looking at the condition as follows. Assume a perfectly balanced multiphase group of p phases in which all harmonics below $p \pm 1$ are suppressed. If one six-phase unit is shut down, the harmonics appearing on the system apart from the $p \pm 1$ harmonics correspond to those that would exist if this six-phase unit were operating alone and carrying its normal load.

As the number of phases in a multiphase group is increased, the benefits obtained are limited by the foregoing factors. With a large number of units, it is more difficult to maintain all the conditions required to obtain the results that are theoretically possible.

CHARACTERISTICS OF POWER-SUPPLY SYSTEMS

Considerable attention has been given to the manner in which the characteristics of the rectifiers affect the magnitude of the harmonics produced. The characteristics of the power system are also important in determining the wave-shape distortion, particularly at a distance from the rectifier load. The impedances of power equipment such as generators and transformers increase proportionally to frequency and are largely inductive reactances over the frequency range of interest. The impedances presented by transmission lines may be either inductive or capacitative reactances and may vary from one to the other over the frequency range. Therefore, if the power-supply system is extensive the impedance looking back into it from the rectifier will be a very complex function of frequency.[10] The wave-shape distortion a rectifier would cause in these circumstances would differ markedly from what it would be if the system impedance were uniform over the frequency range or varied in a simple manner with frequency.

OTHER CONTROL MEASURES

Other means of controlling the wave-shape distortion are feasible in certain situations. If exposures of communication circuits exist only in some parts of the power system, it may be possible to operate the system in such a manner that the wave-shape distortion does not extend to that part or is reduced to such an extent

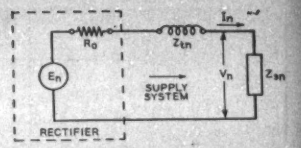

Figure 5. Schematic diagram of circuit on which rectifier harmonic voltages are impressed (phase-to-neutral equivalent circuit)

E_n—Harmonic voltage produced by the rectifier
R_0—Rectifier internal resistance
n—Order of harmonic
Z_{tn}—Rectifier-transformer reactance at the nth harmonic
Z_{sn}—Phase-to-neutral system impedance external to the rectifier transformer at the nth harmonic
V_n—Harmonic phase-to-neutral line voltage due to the rectifier
I_n—Harmonic line current due to the rectifier

that it is no longer troublesome. Usually there are disadvantages to following a plan that impairs the flexibility of the power system, and this means may not be looked upon with favor as a permanent solution. It may be very helpful, however, in the interval pending the application of permanent measures.

In some situations the use of frequency-selective devices or filters in the power-supply system is the best solution. Such devices may be shunt capacitors, series inductive reactors, or any combination of such items. With well-balanced multiphase operation the lowest unsuppressed harmonics are sometimes the chief components of the TIF. Selective devices for these two frequencies will improve the wave shape greatly without being unduly costly.

Sometimes the characteristics of the power system are such that resonance occurs at a harmonic frequency and the magnitude of that harmonic is increased out of proportion to the others. Filters to suppress the one frequency will make marked improvement. A factor to be considered with filters is that in some instances they may be associated with the part of the power system where they are needed, and hence their current and voltage rating usually will be lower than would be required if they were installed at the rectifier.

CO-OPERATIVE ACTION NEEDED

Many rectifier installations do not introduce co-ordination problems. However, when problems do arise they may be serious and widespread. The effects may be manifest over a large part of a power network or they may appear in any part of it. In some cases they appear in remote parts of the system without causing trouble in the vicinity of the rectifier. If the equipment is already operating, co-ordinative measures are apt to be costly and difficult to install, and communication services will be adversely affected in the meantime.

Table II. Relation Between Harmonics in Theoretical Supply-Circuit Current and Number of Rectifier Phases—60-Cycle System

Order of Harmonic	Frequency (Cycles Per Second)	Harmonic Currents in Per Cent of Fundamental for the Following Numbers of Rectifier Phases								
		6	12	18	24	30	36	48	60	72
5	300	20.0	0	0	0	0	0	0	0	0
7	420	14.3	0	0	0	0	0	0	0	0
11	660	9.09	9.09	0	0	0	0	0	0	0
13	780	7.69	7.69	0	0	0	0	0	0	0
17	1,020	5.88	0	5.88	0	0	0	0	0	0
19	1,140	5.26	0	5.26	0	0	0	0	0	0
23	1,380	4.35	4.35	0	4.35	0	0	0	0	0
25	1,500	4.00	4.00	0	4.00	0	0	0	0	0
29	1,740	3.45	0	0	0	3.45	0	0	0	0
31	1,860	3.23	0	0	0	3.23	0	0	0	0
35	2,100	2.86	2.86	2.86	0	0	2.86	0	0	0
37	2,220	2.70	2.70	2.70	0	0	2.70	0	0	0
41	2,460	2.44	0	0	0	0	0	0	0	0
43	2,580	2.33	0	0	0	0	0	0	0	0
47	2,820	2.13	2.13	0	2.13	0	0	2.13	0	0
49	2,940	2.04	2.04	0	2.04	0	0	2.04	0	0
53	3,180	1.89	0	1.89	0	0	0	0	0	0
55	3,300	1.82	0	1.82	0	0	0	0	0	0
59	3,540	1.70	1.70	0	0	1.70	0	0	1.70	0
61	3,660	1.64	1.64	0	0	1.64	0	0	1.64	0
65	3,900	1.54	0	0	0	0	0	0	0	0
67	4,020	1.49	0	0	0	0	0	0	0	0
71	4,260	1.41	1.41	1.41	1.41	0	1.41	0	0	1.41
73	4,380	1.37	1.37	1.37	1.37	0	1.37	0	0	1.37
Current TIF		1,060	515	913	318	183	140	116	65	26

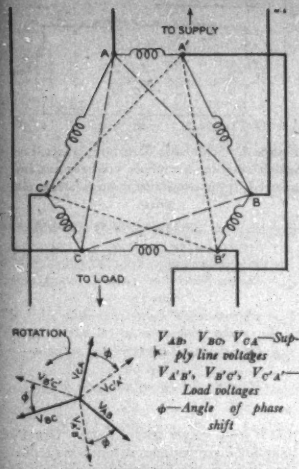

Figure 6. Schematic and vector diagrams for phase-shifting transformer

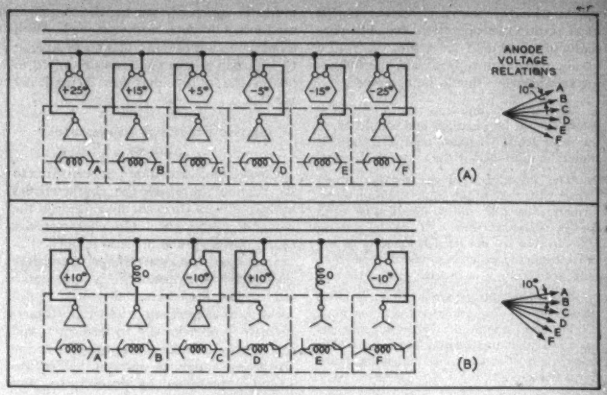

Figure 7. Two methods of providing 36-phase operation with six-phase units and phase-shifting transformers

A. Six like six-phase units
B. Three delta-double-wye units; three wye-double-wye units

To forestall such occurrences it is desirable that all parties concerned in rectifier installations co-operate to investigate at the earliest opportunity the possible effects on co-ordination with communication circuits.

Information on a number of methods of estimating the harmonic voltages and currents produced by rectifiers has been published.[5,6,7] These methods include calculations involving characteristics of the rectifiers and the impedance of the power-supply system at harmonic frequencies. It is necessary to make simplifying assumptions to facilitate calculation, and a very close check between actual and estimated results cannot be expected. Experience does indicate, however, that the methods are useful as a basis of judgment regarding the extent and seriousness of wave-shape distortion.

For many years previous to the war there was extensive growth in power systems, particularly in distribution lines, and communication-circuit exposures were being created on a large scale. During the same period, the wave shape of the power systems was being improved gradually, and this was one factor in making it possible to co-ordinate the two types of circuits without incurring excessive costs specifically for that purpose. The advent of large mercury-arc-rectifier installations has threatened to reverse the trend and is a challenge to the utilities involved.

FUTURE WILL BRING NEW PROBLEMS

About 1938 a large mercury-arc-rectifier installation was put in operation in the United States and excessive noise induction was caused on communication circuits over an extensive area.[8] Development work, in which the manufacturer and the purchaser of the rectifiers and the communication company participated, led to the practical application of multiphase operation as a means of controlling wave-shape distortion. Since that time there has been extremely rapid growth in the installed capacity of mercury-arc rectifiers in electrochemical and electrometallurgical industries. In Eastern Canada alone the installed capacity of mercury-arc rectifiers now totals more than 1,000,000 kw. Multiphase operation has been used widely and has prevented what otherwise would have been widespread co-ordination problems. The types of loads just mentioned are well suited to multiphase operation since it is possible to operate large groups of rectifiers in parallel on both the d-c and a-c sides, and the loads are substantially constant throughout the day. These conditions cannot be expected in all the applications that will be made when rectifiers are available to fill all demands.

As regards the future, new problems can be expected in connection with rectifiers and other types of electronic devices. In addition to use in traction systems and in the electrochemical and electrometallurgical industries, rectifiers have been used widely as a source of direct current for high-power radio stations. It is expected that in the future they will be used wherever conversion from alternating to direct current is required, for example, to supply large d-c motors in steel mills and similar industries. D-c transmission of power has been under development for many years. If it comes into general use, it will involve both rectifiers and inverters, and wave-shape distortion may appear on the a-c systems at each end and on the d-c link. A similar situation will be introduced by electronic frequency changers used either to supply higher-frequency power for industrial purposes or to interconnect power systems of different frequencies.

We do not know the solutions to all these problems or even the precise nature they will take. What can be stated definitely, however, is that the problems can be solved and that the best solutions will be obtained if all parties concerned co-operate wholeheartedly to that end.

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X—Goals in Engineering Education

WILLIAM E. WICKENDEN
FELLOW AIEE

The engineering profession will find it hard to rise above its educational source, and there is no magic through which education can rise above its teachers, declares this educator. More emphasis on the humanistic studies, more time devoted to fundamental science, and a basic analysis of the engineering method furnish the framework of the undergraduate course he proposes.

THIS WAR has made crystal gazers of us all. If each of us were granted a single look into the magic ball, the question most of us would ask would be this: "What does the future hold for the youth of today?" This is a question to keep educators humble—if they need one—but it is the concern of us all. The news columns reflect it. Let any of the oracles of the educational world speak forth—a Butler, a Conant, a Hutchins, or a Compton—and only the President himself commands a wider hearing. The world of education is a world in conflict; it has been so ever since education was invented. Aristotle speaks of the disputes of his day—whether reasoning power, or morals, or useful knowledge, or virtue, or a sense of excellence was the object of education. The moral is that we shall plan our postwar goals provisionally and pragmatically and beware of educational panaceas.

ENGINEERING EDUCATION A SUCCESS

Engineering education stands out in the world of today as a conspicuous success. Let the world judge, if it will, by the lofty mark the poet Milton set, "I call, therefore, a complete and generous education that which fits a man to perform justly, skillfully, and magnanimously, all the offices, both public and private, of peace and war." Milton wrote in the 17th century, in that golden age of generalists. The genius of our age is not Baconian universality; it is rather Einsteinian specialization. We judge education accordingly.

Has the engineer done his job *justly*? Has he stood between capital and labor, between the employer and the employee, between the producer and the consumer, between public welfare and private gain, and served with reasonable impartiality the interest of them all? Not always, not perfectly, to be sure, but soundly and consistently, *yes*. He has done his job just as incorruptibly in the Tennessee Valley Authority or at Grand Coulee or in New Deal bureaus as in the citadels of private enterprise. On the score of *justly*—in Milton's rating scale—we can give him definitely better than an average score.

The second scoring point is *skillfully*. The engineer has always been the chief reliance of American military strategy. A British writer in a recent *Harper's* points out that from the days of George Washington until now our military history has not been written in such heroic episodes as the holding of Thermopylae, or in Napoleonic swiftness of maneuver and suddenness of striking power, or in dramatic charges of a light brigade at Balaclava, but in standing the enemy off while we build up such overwhelming material striking power and such command of the lines of supply that we are at last able to strike the blow which cannot be parried. American engineering has answered that question of *skillfully* in a way that can never be forgotten. The god of war is on the side of the heaviest industrial potential and the best organized lines of supply.

Finally, what about *magnanimously*? Here is a word which means "high-souled, above petty feelings." For a specialist like the engineer magnanimity really means being a good teammate. Does he insist on being captain or will he play just as well in a secondary capacity? Will he let the team have the credit, or insist on the spotlight for himself? Can he applaud what men of other training and gifts contribute—the lawyers, the accountants, the economists, the specialists in public relations, and the politicians—or does he think the whole team should be engineers like himself? Will he put his work above his pay, his standards of excellence above a cheap expediency, his pride of achievement above applause, his integrity above a dubious fee or a shady profit? The world knows the answer—rate the engineer high under the item *magnanimously*.

CONTRIBUTION TO ARMED FORCES

Engineering education has given to industry and the Armed Forces not a slender caste, but strength of numbers; to numbers it has added an elite of advanced scientific skill; to skill in research it has added resourcefulness in invention; to inventive power it has added the priceless ability to get things done. To technical skill it has added a growing capacity for administration. Its graduates have been soundly oriented. They have been able to keep their poise amid the turmoil of economic conflict and social controversy.

To all their normal and special war training functions engineering colleges have added an invaluable contribution to the mobilization of war effort on the laboratory front. This is a public function of the engineering colleges which deserves to be far more widely recognized and supported—that of maintaining at all times a great liquid pool of scientific equipment and research skill which can be mobilized in any emergency, be it local or global, for the service of industry, or civil government or the Armed Forces. The colleges are thus the indispensable mobile arm of our entire scientific and technical establishment.

Beyond all doubts engineering education has been a success. With all the models to choose from, the Army and the Navy unhesitatingly have chosen the technological model, to the dismay of the liberal faculties who had assumed that theirs was the only "complete and generous" education, for

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William E. Wickenden is president of the Case School of Applied Science, Cleveland, Ohio.

undergraduates at least, that met Milton's standards. Every present indication of the day when millions of war veterans will return to the unfinished business of their education points to a crowding of the technological schools beyond all previous records.

TOMORROW'S ENGINEERING EDUCATION

Tomorrow's engineering education is going to be good general education; it is going to be good humanistic education, as well as good scientific education, and good technical education. In the colleges more time and relatively much more emphasis will be given to humanistic studies—English, history, social institutions, economics, and psychology—and to the sources of enjoyment and of spiritual enlightenment in literature, the drama, the fine arts, religion, and philosophy. Less than a year of the undergraduate period devoted to this realm—distributed, of course, through the whole curriculum—will be scored as under par. By the same token, more time and relatively more emphasis will be devoted to fundamental sciences. More men will study beyond calculus; two years will be devoted to general physics instead of one and possibly to chemistry as well. Combining the sciences and the humanities, the average engineering student will receive fully $2\frac{1}{2}$ years of work that will be accredited in any liberal-arts college in the land.

There are solid, even compelling, reasons for this effort to give the young engineer the soundest possible general education, and yet to do it within the framework of the engineering curriculum. For one thing, he is to be not only an engineer but a citizen, sharing equally with all other educated men the responsibility for national security, civic welfare, cultural advancement, and organized community life. The sooner we in the United States rid ourselves of the idea that these are the special responsibilities of an elite group, to be trained in colleges set apart from the working concerns of life, the better. Then too, the engineering graduate is not only a scientific technician but a prospective executive. Fifteen years after graduation three out of four will be engaged principally in directing the work of other men. Whether as expert technicians or as executives, engineering graduates will be working under a professional code which demands not only an ethical standard of personal integrity, but also certain social obligations beyond the range of immediate outcomes of their work. To an increasing degree engineers must hold their own in teamwork with men trained in the social sciences, that is, with economists, sociologists, psychologists, and political administrators. This can come only through the command of a common language and a common standard of values.

On the scientific side, the permanent values in an education are not in details of technique which are growing obsolete before they are incorporated into textbooks, but in principles and relations which are of enduring validity. Slide-valve engines may yield to steam turbines and gasoline engines to jet propulsion, but Newton's laws of motion and the first and second laws of thermodynamics will stand, and engineers are still far from exhausting their potentialities. The chief weaknesses in engineering disclosed by the war are said to be due to inadequate grasp of fundamental physics, and it is a somewhat startling commentary on the scientific foundations laid only a decade ago that so few men who were graduated in that period have been able to master the most recent applications of electronics and of ultrahigh-frequency radiation.

If engineers are to receive as good a humanistic and scientific education as they should, it is inevitable that there will not be enough time left in the undergraduate period to afford both a rounded view of engineering fundamentals—structural, electrical, mechanical, and the like—and a substantial technical grounding in some major branch of engineering application. Pruning becomes inevitable, and judicious pruning calls for a critical evaluation of what is to be kept and what is to be cut away.

MASTERY OF ENGINEERING EDUCATION

The best thinking of engineering educators on this point is that the permanent values of the senior stage of the curriculum do not lie in any detailed knowledge of subject matter or technique, but rather in an introductory mastery of the engineering method. This is a way of using knowledge, rather than knowledge itself. It is a method of analysis, of procedure, and of evaluation, to be applied to new situations, rather than a familiarity with standard solutions already arrived at. It is not a course in any particular subject, but a process that cuts across the various areas of subject matter. It is an active process, applied by the student to problems and projects of the right degree of difficulty, and not a passive process of hearing lectures and witnessing demonstrations. It draws on generic principles and the corollaries derived from them, on the basic assumptions used to make complex situations manageable, on the data of empirical observation, on the codified experience embodied in standards and recorded in handbooks and manuals. It makes use of judgment factors beyond the limits of rational analysis. Finally, it employs the criteria of cost and return which is known by the name of engineering economy. It is this method which distinguishes engineering from science, and it is one way of distinguishing an engineer from a chemist or a physicist.

The detailed technique of engineering practice is a goal that must wait for the postgraduate or the postcollege period. A good many people have argued that the way to meet that problem was to make the engineering curriculum a five- or six-year course. Most educators have come to think that a better job could be done by adding to a four-year course an extension that is tailor-made for the individual after he has discovered his particular needs, rather than something ready-made for all in advance. Until the war broke out, engineering college in the urban industrial centers were growing especially active in part-time and evening graduate work to meet this need. Some industrial concerns have done splendid work in providing means by which young graduates go on in the study of advanced fields of engineering, as well as the usual training courses intended to familiarize college recruits with the organization, personnel, geography, routines, and products of their business.

Now that we have projected a route map for postwar engineering education, let us go back and quickly sketch in some of the details. From all present indications the engineering schools are going to have the call on a high proportion of our ablest young men. This is the time to put admissions on a selective basis. A second reason for doing so is the promise of a large-scale development of a semiprofessional type of technical education in technical institutes, as in New York State, and in junior colleges, as in California. A lot of practical-minded boys who in the past have turned toward the engineering colleges are going to have somewhere else to go, with a better chance of success in a more intensive and more directly practical type of training.

The methods by which the Army and the Navy have selected young men for their college programs have furnished confirming proof of what engineers have long believed, that high-school graduation supplemented by a test of scholastic aptitude is not sufficiently discriminating for the selection of qualified students of engineering. These tests, incidentally, have revealed rather shocking variations in secondary-school preparation in various parts of the country. Measures of scholastic attainment and aptitude which will be more valid for engineering are now being developed in a co-operative project aided by the Carnegie Foundation. These measures, taken in conjunction with greatly improved personnel techniques which can be adapted from the experience of the Armed Forces, give promise of marked gains in the effectiveness of engineering education. These selective-admission practices have an important economic aspect. In the past the average engineering college has graduated less than half the students admitted. The quickest and by far the cheapest way to increase the capacity of engineering colleges to meet rising postwar demands is simply to select better educational risks.

A more discriminating selection of students may give more homogeneous human material, but there still will be wide differences in endowment, preparation, pace,

and intellectual interest. Engineering education will never be really efficient so long as these boys are al run through the same mill. A higher degree of success in reaching a more modest goal would be a wholesome experience for some, while others should be set to far more challenging tasks if their real abilities are to be engaged. The humanistic section is one of the most promising in which to begin. No matter how carefully students are selected for general aptitude and ability, some will enter college with highly developed language skills and with the benefits of travel, observation, and wide reading; others, equally worthy, will be but little removed from alien backgrounds or extremes of native provincialism. Enrichment for the former, through wider excursions into the areas of literature, art, history, and other social studies, and more effective grounding in fundamentals for the latter would seem to be worth-while goals.

Early in the postwar era engineering colleges may find themselves forced to choose between technical specialization and functionally differentiated programs for their upperclassmen. The best thought among engineering educators is that undergraduate curricula should be narrowed down to a few major classifications, corresponding to the dominant arms of the profession. No psychologist can tell whether a boy is better qualified to be a civil or a mechanical or a chemical engineer; what he does think is that one might be able to recognize in a student by the senior year budding promise in such areas as research and development, analysis and design, production and operation, and administration and commercial relations. Let higher orders of technical specialization wait until after graduation and some early experience, would be the psychologist's advice, and give the senior a chance to develop a bit along one of these functional lines.

PROJECT METHODS OF INSTRUCTION

In recent years educators have been growing rather shamefaced about their adding-machine methods of counting up educational credits. In far too many cases the formula has been that 120 or perhaps 140 credits in the registrar's books equals one bachelor of science degree. This gives too much encouragement to the temporary bolting and prompt regurgitation of scholastic fare, soon happily forgotten. The teacher who won out in the competition for the student's time and effort was the one who sent him home with overnight chores to do. We are moving toward project methods of instruction, and overall methods of testing which are concerned with the student's power to do, as distinct from piecemeal measurement of achievement. Engineers may be thankful that they were graduated before the comprehensive examination was invented, but they will like the youngster who can handle one with distinction better when they come to hire him.

In the colleges with real scientific talent on their staffs, organized research has experienced a great boom from the war. Some of this growth will be transient, but the permanent gains still will be notable. Time, indeed, may show it to be the greatest thing that has happened to engineering education in 50 years. For one thing, it transforms the atmosphere of a college from that of a glorified sort of schoolhouse to a place where real things are happening. At its worst, it drains superior talent away from the classroom and leaves the student to the uncertain ministries of the routine teacher. At its best it does something for an engineering school that is closely equivalent to what association with a great hospital does for a medical school. An engineer is a man who spends his life in solving problems. He can best learn this art as a disciple, under men actively engaged in solving problems—real ones, not exercises in the back of a book. Research gives the teacher a ready-to-hand means of balancing scholarship with practice. It offers him exceptional opportunities for professional recognition and prestige. Within reason, it offers opportunities for an earning power which will make the academic world more attractive to men of ability. To the college, it offers means of augmenting equipment and spreading overhead expense. To the nation, it offers the possibility of maintaining a liquid pool of scientific manpower and equipment which may be mobilized quickly in a period of crisis. The task which confronts educators is not merely to assure the continuance of research activity, but to gear it most effectively into teaching activities.

STRENGTHEN COLLEGE FACULTIES

Chief among postwar goals must be the immediate rehabilitation and the progressive strengthening of college faculties. War service is taking a heavy toll of depletion and of exhaustion. Abrupt curtailments of military-training programs and the vacillating policy on student deferments, now turned wholly negative, are tending to a dispersion of forces little less than tragic. Meanwhile virtual cessation of graduate instruction has dried up the normal source of teachers. If thousands of returning veterans crowd into the colleges before these losses can be repaired heaven help the colleges and them. The entire profession will be hit hard by the accumulating deficits in the higher levels of training, and colleges will be ill-financed to compete with industry for such talent as exists.

The plain truth is that these seedbeds of the engineering profession are going to need its protecting hand and that of industry. If you raid them for manpower, you may live to regret it. Colleges must find money somewhere to pay for high-grade leadership. Probably the best way for industry to help is to finance research projects that will keep men of superior talents on college campuses and to encourage colleges to engage engineers and research scientists of distinction as clinical professors for part-time teaching. The profession will find it hard to rise above its educational source, and there is no magic through which education can rise above its teachers. New curricula, expanded laboratories, co-operative plans, new techniques of personnel selection and work evaluation—these things are tools, and they can never be stronger than the hand that wields them.

Out of sheer necessity, engineering colleges will have to put more effective efforts into the development of young teachers. Competition will compel us to catch them young, to give them a vigorous tryout, to work out with them tailor-made plans for their individual development, to stake them through advanced stages of training and experience, and to push them into stimulating relations with the active world beyond our campuses. I cannot imagine a more fascinating and rewarding task for an educational executive, for it is one in which I am sure industry can be induced to give enlightened co-operation, and to which alumni and friends of education can be induced to contribute funds.

Finally, let us take as our goal a profession truly conscious of its destinies. Engineers today are a divided body, vaguely groping for their place in the sun and only half aware of their common responsibilities; yet it is probably no exaggeration to say that no other profession and no other branch of education have had such an opportunity to enlarge their sphere of influence as awaits engineers in the postwar world. The essence of a profession is social trusteeship. A physician is expected not only to be skilled in the arts of diagnosis and of therapy, but also to guarantee in company with his fellow physicians the standards and facilities of the health service offered to his community. A lawyer is expected not only to be skillful in drawing legal instruments, in pleading cases, and in composing disputes, but also to join with his colleagues in guaranteeing the standards of justice in the courts and legislative bodies. One requires of a clergyman not only the services of a spiritual adviser and minister, but also that men of the cloth unite in giving voice to the public conscience and force to public morals. Likewise, an engineer is asked not only to be expert in the technique and economy of materials and energy, of structures and products and utility services, but also to guarantee that society will reap the fruits of scientific advance and technical progress in general wellbeing.

Such a guarantee cannot issue solely from engineering efforts in the laboratory and the plant; it is inseparable from matters of public policy and administration. Shall research be free or regimented? Shall the protection of the patent system

be denied to the fruits of corporate research? Shall the national fiscal policy favor or inhibit capital risks? Shall we be more intent on policing the capital and price structure than on encouraging technological improvement? Shall free enterprise be fostered in areas where great possibilities of technical advance exist? Shall management be always suspect, and labor deemed incapable of doing wrong? Shall natural resources be nationalized? Our professional future and its potential fruitfulness to society are inseparable from these and kindred social issues.

There can be no powerful and unified engineering profession tomorrow unless it is created today in the consciousness of engineering students. We educators must do that job, and you must lend your interest and encouragement. In this hour when the prestige of engineering stands high and when engineering education stands forth, as never before crowned with success, let there be no hypnotic self-satisfaction, no seductive complacency among us. This, gentlemen, is the time to mark up our goals!

Grounding Principles and Practice

II—Establishing Grounds

CLAUDE JENSEN
ASSOCIATE AIEE

GROUNDING has become an everyday electrical term and a very common practice in electrical construction and operation. The primary function of most grounding is to increase safety for life and property. Its secondary function is to improve the operation and continuity of service of electric systems. These two functions are often complementary and compatible.

There are a number of methods for making ground connections. The essential requirements are that they shall be durable, have low resistance, have adequate current-carrying capacity, and be economical to install.

This article is a general treatment of the various types of ground connections, their characteristics, methods for improving ground connections, and methods for measuring ground resistances. It is based on the experiences and developments of the industry.

TYPES OF GROUNDS

In general, ground connections may be divided into two groups or classes. The first comprises water pipes, metal frameworks of buildings, well casings, and other metal structures or materials installed for purposes other than grounding. If located near the equipment or circuit being grounded, they can provide convenient and economical types of grounds.

The other group comprises driven electrodes, buried plates, strips, and conductors, and other kinds of specially designed electrodes. These are intended solely for the purpose of making a ground connection and are installed at, or as near as practicable to, the location where the ground connection is desired.

Claude Jensen is electrical engineer, Copperweld Steel Company, Glassport, Pa.

WATER PIPES

As a means of grounding electric systems, such as secondary lighting services and telephone services, water pipes probably come first from the standpoint of economy. In urban areas, they usually extend over the same area or territory as that covered by the electric-lighting and telephone systems, and are therefore readily accessible at service pipes and at other places. Consequently, ground connections to them are economical in first cost.

Because of the great extent of water-piping systems, they offer good conductance to the flow of current into the earth. In many instances, the resistance of a water-pipe ground connection is of the order of a fraction of an ohm and a value of two to three ohms or more would be considered as excessive. This comparatively low resistance may be attributed mainly to the wide extent of such systems and the tremendous volume of earth affected. In many instances, pipes are many miles in length, and sizes range from the ordinary service pipe to mains a foot or two in diameter or even larger depending upon the water system of the particular city.

This article is the second of five based on a series of lectures on the subject which was sponsored by the power and industrial group of the AIEE New York Section during the 1943–44 season. Various types of ground connections, together with methods for measuring ground resistance, are discussed.

The types of soil in which water pipes are embedded may have a wide range of resistivity values. However, this has relatively little effect on the resistance of the ground connection because of the wide extent of the system. Also, the pipes are usually installed at depths below the frost line where the moisture is relatively permanent and where the resistance is little affected by seasonal variations.

On the other hand, the type of joints used in water-piping systems will affect the resistance. Where lead or screw joints are used for joining together lengths of pipe, these usually provide good metallic connections and the resistance is so low as to be almost negligible. In comparison to this, where joints are made with cement or "leadite," resistances may range from several ohms to several hundred ohms and such systems are consequently not good for electrical grounds. However, water-piping systems are widely used and, in general, are satisfactory for many purposes.

METAL FRAMEWORKS

Structural metal frameworks of buildings which make direct contact with the soil and are dispersed over an extensive area of ground may also be used for ground connections. This type of ground is permitted by various codes as an alternate method of grounding when a water-piping system is not available.

The National Electrical Code states that metal frames of buildings have, in general, a resistance substantially below 25 ohms. This depends on the size of the building, the type of footings, and the soil at the particular location. Tests reported by one investigator gave values of 2.4 and 2.2 ohms for steel frameworks of two relatively large buildings.[1] Resistances of this order

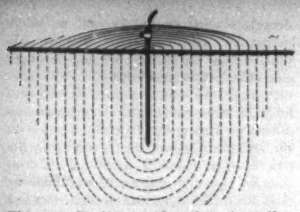

Figure 1. Resistance of earth surrounding an electrode

This may be pictured as successive shells of earth of equal thickness. With increased distance from the electrode, the earth shells have greater area and therefore lower resistance

compare favorably with those of water-pipe grounds and connections to them should provide satisfactory ground connections. However, measurement of resistance is the criterion in determining the suitability of grounds of this type.

WELL CASINGS

Steel pipe used as casings in wells is sometimes used for making ground connections at substations and also in rural areas where a well is located near to the system or equipment being grounded. Usually such pipes extend a considerable distance into the earth and can affect a tremendous volume of earth so that grounds of this type should be comparatively low in resistance. One reference mentions a substation-ground connection to a 14-inch-diameter steel casing 100 feet in length which had a resistance of approximately 1.3 ohms.[2]

In using any of the foregoing methods for making ground connections, it should be remembered that they serve a twofold purpose. One is the original purpose for which the equipment was installed, and the other is its use as a ground connection.

Any changes or alterations in the equipment or facilities as related to the original purpose may affect its use or functioning as an electrical ground. For example, the removal of a water meter would disconnect the water pipes in a building from the service pipe and street mains.

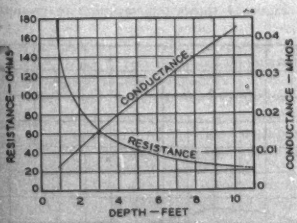

Figure 2. Effect of depth on resistance and conductance of a driven ground for uniform soil resistivity

Table I. Resistances of Different Types of Soil

From Bureau of Standards Technologic Paper 108

Grounds Tested	Soil	Resistance in Ohms: Average	Minimum	Maximum
24	Fills and ground containing more or less refuse such as ashes, cinders, and brine waste	14	3.5	41
205	Clay, shale, adobe, gumbo, loam, and slightly sandy loam with no stones or gravel	24	2.0	98
237	Clay, adobe, gumbo, and loam mixed with varying proportions of sand, gravel, and stones	93	6.0	800
72	Gravel, sand, or stones with little or no clay or loam	554	35	2,700

Certain precautions are therefore necessary to prevent any break in the path to earth. In the case just mentioned, the National Electrical Code requires that if the ground connection cannot be made on the street side of the meter, the water-piping system shall be made electrically continuous by bonding together all parts which are liable to become disconnected.

DRIVEN ELECTRODES

Considering the group or class of grounding electrodes which are installed solely for the purpose of making a ground connection, the driven electrode is used far more than the other types. This results from its numerous mechanical and electrical advantages as compared to other types of installed grounds such as buried plates, buried strips or cables, grids, and so forth. The outstanding advantage is the low cost of driven grounds compared to the other forms of grounds, also the simplicity of driving a rod compared to the task of excavating for and installing buried electrodes. In addition to this, the ground area required for a driven electrode is small, which is a decided advantage in locations where excavation is difficult or where space is limited.[3]

Another important advantage is that the connection between the ground wire and the driven electrode can be made above the surface of the ground, which makes it convenient and easy to inspect

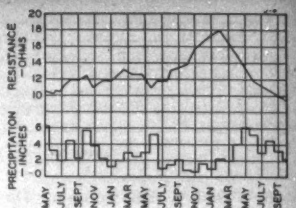

Figure 4. Seasonal variation in resistance with rainfall

the connection or to disconnect the ground lead if it is desired to test the resistance of the ground.

The conductance of a driven electrode compares very favorably with that of other types of installed grounds. It has the advantage that two or more electrodes may be driven and connected in parallel and, for a given cost, it is possible to obtain a much lower resistance with driven electrodes than with other types of installed grounds.

Where the permanent moisture level or a layer of better conducting soil is at a considerable depth below the surface, rods can be driven to a depth far beyond that which would be practical or economical for buried grounds. Furthermore, the use of artificial treatment as a means of reducing the resistance of a ground lends itself more readily to driven electrodes than to the other types.

These advantages of the driven electrode account for its widespread use. However, to secure the best results in practice, an understanding of the general principles and characteristics of driven grounds is necessary.

CHARACTERISTICS OF DRIVEN GROUNDS

Although the earth may be considered as a conductor which has practically unlimited conductance capacity and, on account of its size, negligible resistance, it cannot be assumed that all connections to the earth will have the same characteristics. The electrical conductance of soil is determined largely by its chemical ingredients and the amount of moisture in the soil.

That the resistance of a ground connection is dependent mainly upon the type of soil surrounding the electrode is shown in Figure 1. This is pictured as cylindrical

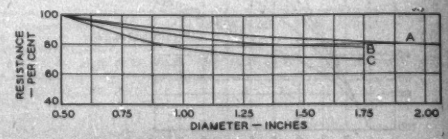

Figure 3. Effect of electrode diameter on resistance of a driven ground

A—From Bureau of Standards technologic paper 108
B—Average of Underwriters Laboratories tests at Chicago
C—Average of Underwriters Laboratories tests at Pittsburgh

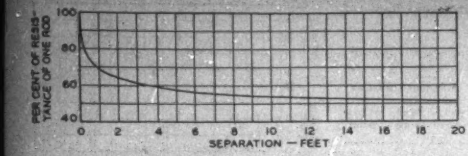

Figure 5. Variation in resistance with distance apart of two electrodes connected in multiple

shells of earth of equal thickness. The greatest resistance is in the shell immediately surrounding the electrode which is the region of smallest cross section at right angles to the flow of current through the soil. Each succeeding shell has an increased cross section. At a distance of eight to ten feet from the rod, the area of the path is so large that the resistance is almost negligible. The resistance varies inversely as the cross section, and therefore, in the area within a few feet from the electrode, where the conducting path is small, the resistivity of the soil is an important factor. Measurements show that 90 per cent of the total electrical resistance surrounding an electrode is generally within a radius of six to ten feet from the electrode.

The wide variation in soil resistance is illustrated in Table I which is based on measurements made by the Bureau of Standards on different types of soil.[4] As will be seen, values as low as 2.0 ohms were obtained in some soils, whereas for others, the resistance was as high as 2,700 ohms. Even wider variations than these are possible.

CONTACT RESISTANCE BETWEEN METAL AND EARTH

The contact resistance between a ground electrode and the soil can be considered as negligible compared to the resistance of the soil itself, for the metals commonly used for driven electrodes. This assumes that the metal is clean and free from paint or grease and that the soil is firmly packed around the electrode.

The contact resistance between metal and soil has been determined from tests by the Bureau of Standards.[4] In these tests, several samples of earth were used, each of which was thoroughly mixed before testing, to insure as uniform resistivity as possible. Tests were made by placing different quantities of soil in a cylindrical glass vessel having an iron bottom, compressing it by forcing an iron piston down upon it and measuring the electrical resistance between the piston and the metallic bottom. These measurements indicated that the effect of contact resistance between clean electrodes and earth, when firmly pressed together, is negligible, since the readings showed the same specific resistance for different depths of soil in the cylinder.

EFFECT OF DEPTH

The depth to which an electrode is driven is probably the most important factor affecting its resistance. There are several reasons for this. First, the volume of soil affected increases directly with the length of electrode below the surface, and second, the soil resistivity usually decreases with depth by virtue of the increased moisture content.

Figure 2 shows the variation of resistance with depth of a driven electrode. This curve was plotted from calculated data assuming soil with uniform resistivity.[4] Although this is a theoretical curve, it has been checked and verified experimentally by various investigators, with only slight inconsistencies due to nonuniformity of the soil.

In actual practice, soil is seldom of uniform resistivity and so, practically, the curve shows only what minimum depth in conducting soil it is desirable to reach. For example, it will be seen that the decrease in resistance is small for each additional foot greater than about eight feet. Assuming that relatively permanent moisture is reached at this depth, it would appear that eight feet would be an economical depth. However, where the resistivity decreases with depth, as well as where permanent moisture exists at some distance below the surface, the use of longer electrodes is advantageous.

A useful curve in analyzing the effect of length is the conductance–length curve as shown on Figure 2. In comparison with the resistance curve, which levels off, the conductance curve is practically a continuous upward sloping line indicating that electrodes longer than eight feet are beneficial.

The length of a ground rod is also of importance in localities where winter seasons are very severe and where grounds must function in winter as well as summer. The resistivity of frozen soil is very high compared to that of soil at normal temperatures.[5] Hence, grounds should extend well below the frost line, otherwise the resistance is apt to vary considerably throughout the year. Even when driven below the frost line, there may be some variation as the upper layers of soil, when frozen, have the effect of shortening the active length of the electrode in contact with soil of normal resistivity.

DIAMETER OF ELECTRODES

The minimum diameter of a driven electrode is determined by mechanical rather than electrical considerations. The usual practice is to select a diameter only large and strong enough to drive it into the soil at a particular location without bending or splitting.

The effect of electrode diameter on the resistance of grounds is shown in Figure 3. Curve *A* is a calculated curve assuming uniform soil resistivity.[4] Curves *B* and *C* represent the average of hundreds of actual measurements on grounds in two different cities.[6] Considering the diameters used commercially today, from curve *A* it will be seen that doubling the diameter from one-half inch to one inch decreases the resistance of a single driven ground by only 9½ per cent.

SOIL RESISTANCE AFFECTED BY SEASONAL VARIATIONS IN MOISTURE

Seasonal changes in ground resistance vary more or less with the amount of rain throughout the year. Ground resistances are likely to be high following a long dry spell and likewise, lower after heavy rains. Figure 4 shows the variation in ground

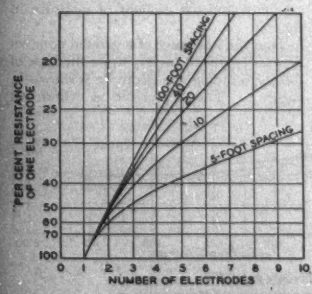

Figure 6. Efficiency of driven electrodes in multiple at various spacings

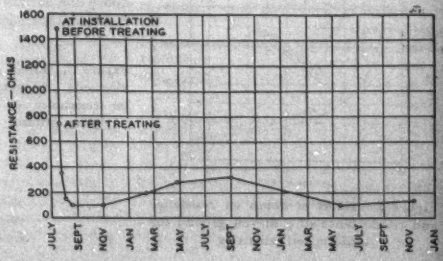

Figure 7. Ground resistance reduced by soil treatment

resistance with precipitation which occurred at one installation.

The normal moisture content of soils ranges from about 10 per cent in dry seasons to around 35 per cent in wet seasons with an approximate average value of about 16 per cent to 18 per cent.[2] Tests by the Bureau of Standards showed that when the moisture content is below 22 per cent, the resistivity increases very rapidly.[5] It may be seen from this that seasonal variation in rainfall can affect the resistance of a ground connection to a considerable extent.

METHODS FOR IMPROVING GROUNDS

Where the resistance of a driven ground connection is very high or in excess of a value considered satisfactory for a particular installation, there are various methods which can be used for improving the resistance of the ground. These are the use of multiple electrodes, soil treatment, a combination of multiple rods and soil treatment, or deep-driven electrodes.

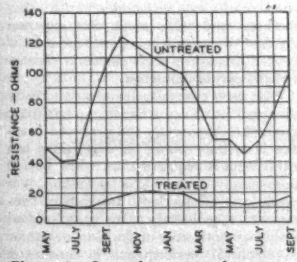

Figure 8. Ground treatment lessens seasonal variation in resistance

MULTIPLE ELECTRODES

One of the most convenient and economical methods is by means of multiple electrodes. When two driven electrodes, well spaced from each other, are connected in multiple, they provide two parallel paths to earth. Since 90 per cent of the total resistance is located within six to ten feet of an electrode, these rods should be spaced far enough away from each other to minimize the tendency for overlapping of the current paths away from the electrodes. The effect of spacing on the resistance of two electrodes connected in multiple is shown in Figure 5.[4]

With wide spacings, each additional driven electrode introduces a new cylinder of unused soil and the combined multiple resistance is decreased by an amount approximately inversely proportional to the number of electrodes; that is, two rods in multiple tend to have one-half the resistance of one rod, three rods, one-third the resistance, and so on.

This direct reciprocal relation is not quite reached in practice, however, as the spacing is necessarily limited and the conducting paths or cylinders surrounding the rods tend to overlap. This point is illustrated in Figure 6. Two rods at 100-foot spacing would have approximately 50 per cent of the resistance of one electrode, but spacings of this order are often impractical. Also, the resistance and reactance of long leads necessary for connecting electrodes at wide spacings would tend to decrease the effectiveness of rods in multiple. However, with spacings of 10 to 20 feet which are generally feasible, the reciprocal relation can be closely approached.

The characteristics of multiple-ground-electrode systems have been discussed in numerous technical articles and papers. In an article by H. B. Dwight,[7] curves are presented showing the relationship between the number of electrodes, the spacing, ground area, conductance and effectiveness. Similar data are also given in an article by J. R. Eaton.[8] This information may be useful in designing station grounds where large numbers of electrodes in multiple are used.

SOIL TREATMENT

Artificial treatment of the soil surrounding a driven electrode is often resorted to as a means of lowering the resistance of a ground. Substantial reductions in the resistances of electrodes already installed may be accomplished by dissolving in the moisture normally contained in the soil some substance which is highly conducting in its water solution.

There are a number of chemicals suitable for this purpose, such as sodium chloride, magnesium sulphate, copper sulphate, and calcium chloride. Other chemicals which have been investigated are iron sulphate, sodium nitrate, potassium nitrate, and ammonium sulphate. The selection is largely dependent upon cost, availability, and the corrosive properties of the chemical. Common salt and magnesium sulphate are most generally used.

Chemical treatment can affect reductions in soil resistance anywhere from 15 per cent to 90 per cent. The benefit which can be gained is dependent mainly upon the kind and texture of the soil. Figure 7 illustrates the results obtained for one installation. The percentage reduction in this case is rather high and typical for grounds having high resistances. Grounds of lower resistance may be improved by treating but not in the same proportion.

In addition to lowering the resistance of a ground, soil treatment also smooths out seasonal fluctuations, as shown in Figure 8. The curve for the treated ground shows some variation, but it is not nearly so great as for the adjacent untreated ground.

Chemical treatment has one disadvantage in that its effect is not permanent, the solutions being gradually carried away and dissipated by the natural drainage in the soil. The rate of dissipation is dependent upon the porosity and type of soil and the amount of rainfall. Renewal of the treatment may be necessary after a few years or when periodic tests indicate a constant increase in the resistance. This is illustrated in Figure 9 which shows that the effect of soil treatment was completely dissipated after a period of five years and the resistance was then the same as that of an adjacent untreated rod.[9]

METHODS OF APPLYING SOIL TREATMENT

A typical method for installing soil-treating material is to place the chemical in a circular trench around the electrode as shown in Figure 10. This is effective in that it not only prevents direct contact of the chemical with the electrode, but also the materials are advantageously placed so that the solution spreads through and affects a greater volume of soil than when placed directly around the electrode.

Certain chemicals, such as common salt, calcium chloride, copper sulphate, and iron sulphate when placed in direct contact with electrodes and in the presence of moisture, tend to cause corrosion of the electrode. However, by placing them in a trench as shown, they do not come into direct contact with the electrode. As the crystals are gradually dissolved by rainfall, the solution permeates through the soil to the electrode and since the solution is relatively weak compared to the concentrated chemical, the corrosive action is minimized.

Another method of treating which has been used is to place the chemical in a tile pipe 16 to 18 inches long alongside the electrode as shown in Figure 11A. This method is convenient where space is restricted. It is also effective in preventing direct contact of the treating material with the electrode. However, with this method,

Table II. Low Resistances Obtained With Deep-Driven Grounds

Description of Soil	Length of Sectional Rod, Ft	Ground Resistance Measured at Various Depths When Installing Rod								Remarks
		8 Ft	16 Ft	24 Ft	32 Ft	40 Ft	48 Ft	56 Ft	64 Ft	
Clay	64	29	14	8	4.5	3	3	3	3	
Clay	48	270	230	48	13	10	6			
Clay	32	140	45	15	5.5					
Clay	40	75	45	21	8	4				
Clay	48	50	23	18	8.5	5.5	2.5			
Sand and clay	32	200	22	11	9					Struck hard layer, 28 feet
Clay	32	45	30	9	2					Struck stone at 24 feet
Sand	40	200	55	40	33	16				Salted ground

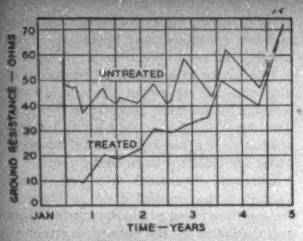

Figure 9. Variation of resistance to ground with time for adjacent electrodes

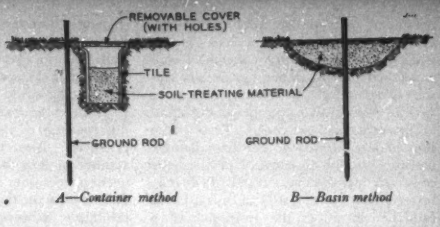

Figure 11. Container and basin methods of soil treatment

the chemical is more concentrated and at least, initially, is not so effective as the trench method.

A third method which has been used is to place the chemical in a basin directly around the electrode as shown in Figure 11B. The objection to this method insofar as corrosive chemicals are concerned has been mentioned previously. Where chemicals have relatively little or no corrosive effect on the electrode, such as when magnesium sulphate is used, the basin method is applicable.

In using any of these methods, it is advisable, particularly during dry periods, to flood the ground thoroughly with water after installing the chemical, so that the solution immediately will start penetrating into the soil. Otherwise, some time may elapse before sufficient solution resulting from normal precipitation permeates through the soil to lower the resistance of the ground.

MULTIPLE RODS AND SOIL TREATMENT

In cases where it is necessary to overcome exceedingly high ground resistances, a combination of multiple electrodes and chemical treatment of the soil is often very effective.

DEEP-DRIVEN GROUNDS

Where a single electrode of ordinary length has an extremely high resistance, the use of deep-driven grounds is often helpful in obtaining lower ground resistances. For example, Figure 12 illustrates graphically the relation between the character of the soil and the resistance at one ground installation. In this case, a ten-foot rod driven in sandy soil had a resistance of 250 ohms. It would have taken something over five ten-foot rods in multiple to approach a 50-ohm ground. However, by extending the ground rod through the sand, it was found that the resistance decreased substantially at about 15 feet depth, and a value of 50 ohms was obtained with a single 20-foot rod. This is a typical example of where deep-driven grounds can be helpful and economical.

For grounds requiring electrodes from 15 to 20 feet in length, it is possible to use rods of a single continuous length. However, the handling and driving of long rods is somewhat of a problem and sectional rods provide a convenient and practical method for installing deep grounds.

One type of sectional rod is made in sections eight or ten feet long of various diameters and with threads at both ends. In practice, the first section is driven using a coupling and a driving bolt at the top end. When this is driven to the ground line, a second section is coupled to the first and the driving continued. In this way, long rods are handled nearly as easily as ordinary-length rods.

Table II shows some typical resistance readings obtained with sectional rods and illustrates good applications for deep-driven grounds. In the second example, for instance, a 16-foot rod had a resistance of 230 ohms. By extending the depth to 24 feet, the resistance dropped to 48 ohms, indicating that the rod had penetrated into the lower resistivity soil. With a 48 foot-rod the resistance of the ground was reduced to six ohms.

A typical example of the use of deep grounds is cited by one power company which uses sectional rods in lengths up to 100 feet for improving the resistances of transmission-tower grounds. These have been effective in reducing the resistance to the order of five to seven ohms per structure.[10]

BURIED PLATES

The use of buried metal plates as a means of grounding electric systems has been confined largely to station grounds. However, the use of this type of ground connection appears to be decreasing which is probably due to the fact that the desired results can be obtained with other methods and with much less expense. As there are cases where plates are used, a brief discussion of their electrical characteristics may be of interest.

The same general principles as already discussed for driven grounds apply to plate grounds. Apparently the preferred practice is to bury plates on edge, since less excavation is required than when buried horizontally. Also when backfilling, it is possible to obtain more satisfactory contact with the soil as the earth can be packed firmly on both sides of the plate. Insofar as electrical performance is concerned there apears to be little difference between the resistance of a plate when buried on edge or when laid horizontally.

VARIATION OF RESISTANCE WITH DEPTH

The curve showing variation of resistance with depth of a plate electrode is similar to the curve for the resistance of two driven electrodes in multiple. (See Figure 5.) Assuming uniform soil resistivity, the resistance decreases rapidly with the first few feet increase in depth and then more slowly, approaching a relatively constant value. Consequently, for plates of ordinary size—that is, of areas say from 10 to 20 square feet—the depth in conducting soil should be from five to eight feet since greater depths would

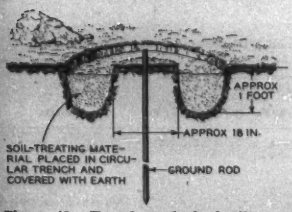

Figure 10. Trench method of soil treatment

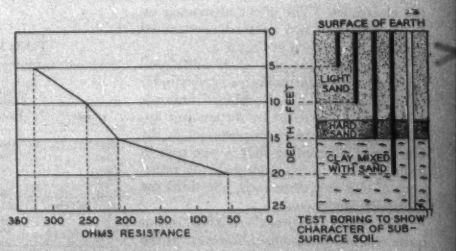

Figure 12. Deep grounds effective in lowering resistance

normally not show any appreciable decrease in resistance.

VARIATION OF RESISTANCE WITH AREA OF PLATE

The resistance of a plate ground is dependent upon the area of the plate, or more correctly stated, on the extent or over-all dimensions of the plate, since the volume of affected soil is the actual determining factor. The variation of resistance with the size of plate is illustrated in Figure 13. This curve is calculated for a circular plate assuming uniform soil resistivity.[4] It will be noted that quadrupling the area of such a plate approximately halves the resistance. This same relation holds approximately true for rectangular shape plates, although because of the nonhomogeneity of the soil, this should be taken only as an indication of the relationship mentioned and not as a check upon it. This curve also shows that increasing the area of a plate beyond 25 to 30 square feet does not result in an appreciable decrease in resistance. Consequently, where plate electrodes must be used, it would require much less labor and material to install two small plates at a distance from each other and connect them in multiple than to install one equivalent large plate.

BURIED STRIPS

Where bedrock is near the surface of the ground, it is frequently out of the question to drive electrodes or to dig deep enough to make an effective ground connection with plates. In such places, the ground is apt to be very dry, particularly during periods of drought, as the soil is not deep enough to permit the storage of moisture during wet seasons. The best procedure under such circumstances is to make a ground connection by burying narrow strips of metal, solid wire, or cable in trenches dug as deep as the rock layer will permit. Because of the high resistivity of the soil which is encountered in dry seasons, it is necessary to have a ground connection of considerable extent, and metal in the form of strips, wires or cables, offers the most efficient method.

VARIATION OF RESISTANCE WITH LENGTH

That an extensive length of metal is required for obtaining a ground connection with low resistance may be seen from the curve shown in Figure 14. This is a theoretical curve based on uniform soil resistivity.[4] Actual measurements which have been made are substantially in agreement with this curve allowing for inconsistencies in the resistivity of the soil existing at the particular location.

It appears from this curve that if the length of the strip is doubled, the resistance is approximately halved. This ratio assumes strips buried in a straight line. If the strips are curved or coiled, the resistance would tend to be higher as the affected soil would be less. With long leads, reactance is also a particularly important factor when dealing with lightning. Consequently, the use of a number of strips in parallel, but well spaced from each other, is usually preferable to one extra-long strip.

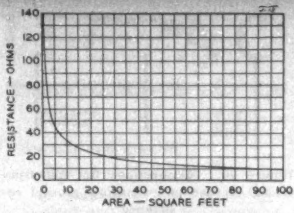

Figure 13. Variation of resistance of a circular plate with area, assuming uniform soil resistivity

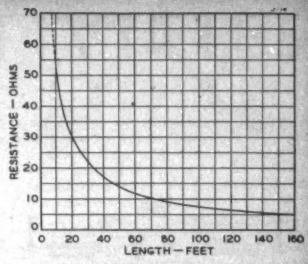

Figure 14. Variation in resistance of a strip electrode with length, assuming uniform soil resistivity

VARIATION OF RESISTANCE WITH DEPTH

Where bedrock exists near the surface of the ground, the depth at which the strip of metal can be buried is necessarily limited. However, where this is not the case and this type of ground is indicated, the relation between depth and resistance may be of interest. Tests by the Bureau of Standards show that the decrease in resistance for a variation in depth between the minimum permissible on account of cultivation—about 18 inches—and the maximum to which it would be practicable to bury an electrode—say three feet—is only about five per cent assuming uniform soil resistivity. Also, the effect of conductor size is extremely small within the range normally used for this purpose.[4]

GRIDS

Grid systems consisting of copper cables buried about six inches in the ground and forming a network of squares are sometimes used at generating plants or substations. The purpose of this grid is to provide equipotential areas throughout the entire station plot, thus avoiding any gaps where differences in potential would be hazardous to life and property.

Such a system usually extends over the entire station yard as well as some distance beyond the fence which surrounds the buildings and equipment. The spacings of the conductors, and therefore the size of the squares, will vary with the different installations. However, cable spacings of 10 to 12 feet have been used at some locations. All crossing points of the cables should be securely bonded together and the entire grid system tied in with the station ground. Also, all structural steel work and equipment are tied in with this network to prevent any differences in potential between these and the ground.

Protective systems of this type, as well as low-resistance grounds, are effective at stations because of the potential gradient which might otherwise result from high fault currents. The cost of installing such a grid system may be rather high because of the amount of labor involved, but the hazards to life and value of the property involved may justify such installations.

COUNTERPOISE

The counterpoise is used extensively in the United States for improving the lightning protection afforded by overhead ground wires on high-voltage transmission lines. This is an application of the buried-strip type of electrode, although round solid wires or stranded cables are generally used rather than strips.

Its usual application is in districts having high-resistance soils, such as sand or rock formation where a supplementary grounding system may be required. It is beneficial in reducing the impedance of the ground connection and in increasing the capacitance coupling with the conductors. It makes use of the widely distributed contact to the soil similar to a number of ground rods in parallel.

Two different arrangements of counterpoise wires have been employed, the continuous type and the radial type. The continuous counterpoise consists of a conductor or conductors buried under the transmission line from end to end of the line or at certain sections of the line and interconnected with the ground wire at all supporting structures. A method commonly used for installing such a counterpoise is by means of a cable-laying plow which places the wire in the ground at various depths down to as low as three feet beneath the surface.

The radial type of counterpoise consists of a number of wires extending radially from the grounding point. The number and length of the radial counterpoise wires will depend on the requirements at the particular location. Soil conditions, the importance of the line, and installation costs must all be considered in determining the extent of counterpoise installations.

Soil conditions along a transmission right of way may vary widely and one particular method of grounding may not be suitable for the entire line. A practical procedure is to make tests at each location

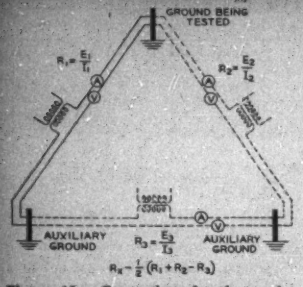

Figure 15. Connections for three-point method of measuring ground resistance, using a-c ammeter and voltmeter

along the line and with the aid of the resistance data obtained, grounding methods can be selected which best suit the requirements. With this plan, low resistances can be obtained at the least cost.

METHODS OF MEASURING RESISTANCE OF GROUND CONNECTIONS

The proper operation of ground connections, like other electric equipment, is dependent largely on well planned testing and maintenance. The resistance of a ground connection should be measured at the time of installation and this should be followed by check tests at regular intervals. Usually precision in such measurement is not required, as it is necessary to know only whether the resistance is of the order of 1 ohm, 10 ohms, 100 ohms, or 1,000 ohms. These values are indicative of whether the ground is satisfactory for the particular installation or whether improvement is necessary.

There are various methods for testing the resistance to earth of installed ground connections. They are similar in that two independent auxiliary electrodes are used in addition to the one under test. These auxiliary electrodes should be placed at a distance remote enough from the ground under observation and from each other so that each ground is independent of any proximity effect of the other two grounds.[11]

The principles used in the measurement of ground resistances are essentially the same as those used for measuring other types of electrical resistances. However, for purposes of discussion, the various methods for measuring ground resistance have been grouped into three general classes which are described herewith.

THREE-POINT METHOD

With the commonly known three-point method, the resistances of the electrode under test and the auxiliary electrodes are measured two at a time in series. A voltmeter and an ammeter are used for making the measurements. Either alternating current of commercial frequency or direct current supplied from an available circuit

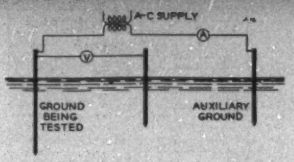

Figure 16. Connections for fall-of-potential method of measuring ground resistance

or from a storage battery may be used. The diagram of connections shown in Figure 15 is applicable when using alternating current. The connections for direct current are similar, but certain precautions as explained later are required. After the three series measurements are made, the unknown resistance is solved by means of the formula

$$R_x = \tfrac{1}{2}(R_1 + R_2 - R_3)$$

A Wheatstone bridge operating on alternating current at 1,000 cycles per second and with a headphone as a detector to determine the point of balance is also applicable with the three-point method. Another method would be to use a direct-reading self-contained ohmmeter.

To obtain a fair degree of accuracy with the three-point method, the resistances of the auxiliary electrodes should be of the same order of magnitude as that of the unknown, otherwise small errors in the individual measurements may result in a large error in the computed resistance.

Stray direct currents have little or no effect on the readings when using alternating current. However, if stray alternating current of the same frequency as the test current is present, this may introduce an error.

When direct current is used for measurement purposes, the effect of stray alternating currents is eliminated and the effect of stray direct currents can be minimized by reversing the test current. Polarization is also a factor when direct current is used and the formation of gas at the electrodes may give a false indication. Taking two readings by reversing the current polarity helps to correct this condition. The current should be applied for short periods only, or just long enough to obtain the readings.

FALL-OF-POTENTIAL METHOD

Another method for measuring ground resistance is based on the fall-of-potential principle. This involves the passing of a known current through the electrode under observation and one of the auxiliary electrodes. The drop in potential between the former and the second auxiliary electrode is then measured and the ratio of this voltage drop to the known current will indicate the resistance to ground. The diagram of connections for this method using alternating current for test is shown in Figure 16. By using a voltage measuring device which has a high impedance, the resistance of the potential electrode will have no appreciable effect on the accuracy of the measurements. The determination of ground resistance by this method may be made with an ammeter and voltmeter or with self-contained instruments which are based on this principle and furnish direct readings of resistance.

RATIO METHOD

In a third method for measuring ground resistances, known as the ratio method, the series resistance of the electrode being tested and an auxiliary electrode is determined by means of a Wheatstone bridge. A slide-wire potentiometer is shunted across these two ground connections and the detector is connected between the sliding contact and the second auxiliary electrode. In this way, the ratio of the unknown resistance to the total resistance of the two electrodes in series is obtained, and the required value is determined by multiplying this ratio by the series resistance obtained in the first measurement.

Measurements by this method may be made by using a bridge and a calibrated slide-wire potentiometer for obtaining the ratio, or by self-contained instruments which give direct readings.

PORTABLE GROUND-TESTING INSTRUMENTS

A portable ground-testing instrument provides the most convenient and satisfactory means for measuring the resistances of grounds. It is self-contained, easy to operate, and the resistance is indicated directly on a dial located on the panel of the instrument. The measurement is made with one setup and when desired the whole operation can be handled by one man. When any program of ground testing is planned, the use of one or more of these instruments is recommended, as the convenience and saving in labor will more than justify their cost.

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INSTITUTE ACTIVITIES

Official Nominees Announced for 1945–46

W. E. Wickenden, president, Case School of Applied Science, Cleveland, Ohio, was nominated for the AIEE presidency for the year 1945–46 by the national nominating committee at its meeting in New York, N. Y., January 23, 1945. Others named on the official ticket of candidates for the Institute offices that will become vacant August 1, 1945, are:

For Vice-Presidents

E. S. Fields, vice-president, Cincinnati (Ohio) Gas and Electric Company (Middle Eastern District, number 2).

H. B. Wolf, superintendent of maintenance, Duke Power Company, Charlotte, N. C. (Southern District, number 4).

L. M. Robertson, transmission and station engineer, Public Service Company of Colorado, Denver (North Central District, number 6).

F. F. Evenson, consulting engineer, San Diego, Calif. (Pacific District, number 8).

F. L. Lawton, assistant chief engineer, Aluminum Company of Canada, Montreal, Quebec (Canada District, number 10).

For Directors

J. M. Flanigen, distribution engineer, plant accounting, Georgia Power Company, Atlanta.

J. R. North, assistant electrical engineer, Commonwealth and Southern Corporation, Jackson, Mich.

W. C. Smith, engineer of Pacific District, General Electric Company, San Francisco, Calif.

For National Treasurer

W. I. Slichter, professor emeritus of electrical engineering, Columbia University, New York, N. Y.

The nominating committee, in accordance with the constitution and bylaws, consists of 15 members, one selected by the executive committee of each of the ten geographical Districts, and five selected by the board of directors from its own membership.

The constitution and bylaws of the Institute require publication in *Electrical Engineering* of the nominations made by the national nominating committee. Provision is made for independent nominations as indicated in the following excerpts from the constitution and bylaws:

Constitution

Section 31. Independent nominations may be made by a petition of twenty-five (25) or more members sent to the national secretary when and as provided in the bylaws; such petitions for the nomination of vice-presidents shall be signed only by members within the District covered.

Bylaws

Section 23. Petitions proposing the names of candidates as independent nominations for the various offices to be filled at the ensuing election, in accordance with article VI, section 31 (Constitution), must be received by the secretary of the National Nominating Committee not later than March 25 of each year, to be placed before that committee for the inclusion in the ballot of such candidates as are eligible.

On the ballot prepared by the national nominating committee in accordance with article VI of the Constitution and sent by the national secretary to all qualified voters during the first week in April of each year, the names of the candidates shall be grouped alphabetically under the name of the office for which each is a candidate.

BIOGRAPHICAL SKETCHES OF NOMINEES

To enable those Institute members not personally acquainted with the nominees to learn something about their engineering careers and their qualifications for the Institute offices to which they have been nominated, brief biographical sketches are scheduled for inclusion in the "Personal" columns of the March issue.

Buffalo and Detroit Technical Meetings Canceled

In compliance with the recently announced wartime ban on conventions, the AIEE board of directors has canceled the North Eastern District technical meeting scheduled to be held April 25–26, in Buffalo, N. Y., and the summer technical meeting scheduled for June 25–29 in Detroit, Mich. This action was taken at the regular meeting of the board held during the winter technical meeting in New York, N. Y., which was drawing to a close as this issue went to press.

The Institute's technical program and publication committees are planning to continue the publication of technical papers in *Electrical Engineering* and AIEE *Transactions* and are devising a plan whereby discussions may be submitted by mail. Details will be announced later.

Index Pamphlet for 1944 Delayed

The annual index to *Electrical Engineering* and *AIEE Transactions*, in recent years distributed as Section 2 of the February issue of *Electrical Engineering*, has not yet become available for material published in 1944 because of the time required for production of an unusually large *Transactions* volume. As a single index pamphlet covers both *Electrical Engineering* and *Transactions* it cannot be published until the *Transactions* is completed.

Approximately twice as many technical papers and discussions were approved for publication in the latter half of 1944 as in the same period of 1943, and the increased quantity of material together with other wartime difficulties has made impossible the maintenance of former production schedules.

SECTION • • • • •

AIEE Boston Section Expands Technical Groups

On the basis that the individual member can derive much value from the discussion and question type of meeting of a small interested group, the incoming AIEE Boston Section executive committee for 1944–45 has announced its decision to expand the technical groups to include four basic subjects for the coming year. These groups, with their chairmen, are: electronics, T. S. Gray, Massachusetts Institute of Technology; electrical machinery, F. B. Haeussler, General Electric Company; insulation, W. I. Middleton, Simplex Wire and Cable Company; and transmission and distribution, J. F. Archibald, Boston Edison Company. Ex-officio members of the technical group committee are: chairman of Section, A. L. O'Banion; secretary-treasurer, R. E. Muehlig; and chairman of meetings committee, C. T. Burke. R. G. Porter, Northeastern University, Boston, Mass., will act as general chairman.

The Boston Section executive committee and membership had felt for some time that the regular meetings of the Section were, in general, of such a nature that they did not offer a large enough concentration in the technical field for the various groups composing the membership of a large section. On this assumption, two meetings of a technical group composed of men in the insulation field were held in 1944. The success of these meetings prompted the formation of the four new groups with a 1944–45 program consisting of three meetings for each group, the chairman of each group to organize his own committee and act as chairman of any meetings of his group.

Experience so far with the new technical groups is that, rather than distracting from the regular monthly Boston Section meetings, they have stimulated interest in the Section, and that the attendance at regular meetings has increased. The meetings have demonstrated that for a large Section the maximum value for its membership can be secured by offering a program which includes ample participation in discussion by its members.

PERSONAL • • • •

Zay Jeffries (M '36, F '42) formerly technical director of the lamp division of the General Electric Company has been elected a vice-president in charge of the recently organized chemical department. Doctor Jeffries received the degrees of bachelor of science in mining engineering in 1910 and metallurgical engineer in 1914 from the South Dakota School of Mines and earned the degree of doctor of science from Harvard University in 1918. Doctor Jeffries, who also has been professor of the Case School of Applied Science and consultant for the Aluminum Company of America, joined the General Electric Company in 1914 and was made technical director of the lamp division in 1936. He has been honored with several degrees and medals and is a member of numerous scientific societies. **E. O. Shreve** (A '06) vice-president and chairman of the apparatus operating committee of the General Electric Company, Schenectady, N. Y., has relinquished these duties to become a member of the president's staff in charge of customer relations in New York, N. Y. Mr. Shreve was manager of the company's industrial engineering department from 1926 until he became vice-president in 1934. **R. C. Muir** (A '08, F '36) formerly a vice-president of the executive staff of the company in Schenectady has been made general manager of the apparatus department. Mr. Muir has

been with the company since 1905, except from 1919 to 1922, during which time he was chief commercial engineer of the International General Electric Company. He was appointed assistant to the vice-president in charge of engineering in 1930, manager of the engineering department in 1933, and vice-president in 1934. **Richard Cutts, Jr.** (A '29) formerly meter specialist, Boston, Mass., has been appointed manager of sales of the meter section, West Lynn, Mass. Mr. Cutts was meter specialist for the company's New York district from 1929 to 1937 when he was transferred to Boston. He is chairman of the watthour-meter and demand-meter management committee. **E. J. Boland** (A '29, M '36) of the meter division of the central-station engineering department Lynn, Mass., has been named manager of sales of the aircraft-instrument section. Mr. Boland, a member of the General Electric staff since his arrival in the United States from Denmark in 1926, has been assigned to aircraft-instrument work since the beginning of the war. **H. V. Erben** (M '43) vice-president and manager of the central-station department, has been named assistant general manager of the apparatus department. Mr. Erben has been with the General Electric Company since 1920 and has been manager of the central-station engineering department since 1941. **H. A. Winne** (A'16 M'39) vice-president, has been made manager of engineering for the apparatus department. **D. C. Prince** (A '16, F '26) vice-president, formerly in charge of application engineering, has been given charge of the company's general engineering laboratory. Associated with the General Electric Company since 1914, Mr. Prince has been, in the course of his career, a member of the research laboratory staff, research engineer on switchgears, and manager of commercial engineering. **C. G. Suits** (M '41) formerly assistant to the director of the research laboratory, has been elected a vice-president and appointed director of the research laboratory. Doctor Suits, who graduated from the University of Wisconsin in 1927, has been a member of the laboratory staff since 1930. He became assistant to the director in 1940. Since the war he has devoted his time to war research under the direction of the Office of Scientific Research and Development.

P. C. Smith (A '26) electrical engineer assigned to special work at the New Philadelphia, Ohio, plant of the Westinghouse Electric and Manufacturing Company, has been appointed assistant to the manager of the transportation and generator division, East Pittsburgh, Pa. **J. S. Askey** (A '39) coil and insulation design engineer, and **G. L. Moses** (A '43) insulation development engineer, have been made section engineers in the transportation and generator division.

M. A. Princi (A '36) formerly in charge of experimental testing and special test equipment, General Electric Company, West Lynn, Mass., has been named assistant designing engineer of the aeronautical-instrument engineering division, in charge of the gyroscope section. **R. G. Ballard** (A '42) formerly instrument engineer, has been appointed assistant designing engineer of the aircraft-instrument engineering division, in charge of the general instrument section.

F. E. Terman (A '23, M '34) head of the Government's radio research laboratory, Cambridge, Mass., has been appointed dean of the school of engineering of Stanford University, Calif. Professor Terman received the bachelor of arts degree from Stanford University in 1920, the engineering degree in 1922, and the degree of doctor of science from Massachusetts Institute of Technology in 1924. He joined the Stanford University faculty in 1925 as an instructor, becoming assistant professor in 1927, associate professor in 1930, and professor and head of the electrical-engineering department in 1937. He obtained a leave of absence from this position in 1942 to head the radio research laboratory in Cambridge. He is a member of Phi Beta Kappa and Sigma Xi and a past president of the Institute of Radio Engineers.

R. R. Stoddard (A '38) formerly power engineer, the Philadelphia (Pa.) Electric Company has been appointed industrial engineer for the Fitchburg (Mass.) Gas and Electric Company, the Rockland (N. Y.) Light and Power Company, the Concord (N. H.) Electric Company, the Exeter and Hampton (N. H.) Electric Company, and various other utilities. Mr. Stoddard's headquarters will be at Boston, Mass.

J. W. Sanger (M '42) formerly chief engineer, City of Winnipeg (Manitoba, Canada) Hydro-Electric System has been made manager of the system. Mr. Sanger's early experience was as district engineer, Midland Electric Power Corporation, Staffordshire, England, in 1906. He became associated with the Winnipeg Hydro-Electric System in 1912 as an engineer. He has been chief engineer since 1922.

H. C. Starkweather (M '38) senior electrical engineer, Signal Office, Third Service Command, Baltimore, Md., has been presented with a "Meritorious Service Award" citing him for his efforts in the field of signal communication. The certificate was awarded by Major General Philip Hayes and is signed by Lieutenant General Brehon Somervell and General Hayes.

B. K. Titter (A '32, M '43) formerly chief electrical engineer, the Nicaro Nickel Company, New York, N. Y., has been commissioned a lieutenant in the United States Naval Reserve. Lieutenant Titter had previously received instruction in radar at Brunswick, Me., and Boston, Mass., and is now assigned to radar duties.

W. M. Shober (A '22, M '40) formerly electrical engineer, Aluminum Company of America, located at Alcoa, Tenn., and Burlington, N. J., is now associated with the Allis-Chalmers Manufacturing Company, Milwaukee, Wis., in the electrical department, mixed apparatus division.

W. E. Ross (M '38) manager of the apparatus sales department, the Canadian General Electric Company, Ltd., Toronto, Ontario, Canada, has been appointed Ontario Government representative on the electrical branch of the Association of Professional Engineers of Ontario by the lieutenant-governor-in-council.

William Fondiller (M '15, F '26) electrical-apparatus director, Bell Telephone Laboratories, Inc., New York, N. Y., has been announced as the recipient of the Townsend Harris Medal for postgraduate achievement, awarded annually by the College of the City of New York to an outstanding graduate.

H. A. Moench (A '31, M '38) has been promoted to the rank of major in the Signal Corps of the United States Army. Commissioned a second lieutenant in the Corps of Engineers Reserve in 1929, he was called to active duty with the Signal Corps in 1942.

W. J. Cherones (A '43) formerly chief civilian engineer, central station fire control and computing gunsights department, Army Air Forces Headquarters, Dayton, Ohio, has been appointed instrument engineer for the Roller-Smith Company, Bethlehem, Pa.

H. B. Marvin (A '20, M '43) formerly assistant engineer, general engineering laboratory, General Electric Company, Schenectady, N. Y., will be responsible for special assignments in the tube division, electronics department.

L. M. Smith (M '36) formerly chief electrical engineer, Alabama Power Company, Birmingham, has been appointed director of public relations for that company. Mr. Smith has been with the Alabama Power Company for the past 21 years.

O. W. Eshbach (A '17, F '37) dean of engineering, Northwestern Technological Institute, Evanston, Ill., has been elected chairman of the 1945 Washington Award Commission of the Western Society of Engineers, Chicago, Ill.

L. A. Rebsamen (A '31) manager of the city water and light plant, Jonesboro, Ark., has resigned to go into private business.

OBITUARY • • • •

Paul Martyn Lincoln (A '95, M '98, F '12) president of the Therm-Electric Meter Company, Ithaca, N. Y., and professor emeritus and former director of the school of electrical engineering, Cornell University, died December 20, 1944. He was born in Norwood, Mich., January 1, 1870, and was educated at Western Reserve and at Ohio State universities, receiving from the latter the degree of mechanical engineer in electrical engineering in 1892. He was employed first as testing electrician by the Brush Electric Company, doing some drafting later. The next year, in 1893, he went to the Pittsburgh, Pa., plant of the Westinghouse Electric and Manufacturing Company, where he took the training course of the company. In 1895 he was chosen for the position of electrical superintendent in charge of water power development at Niagara Falls, N. Y., with the Niagara Falls Power Company. Hydroelectric development was in the early stages then, and the amount of power generated, transmitted, and distributed by this first plant was so far in excess of anything accomplished up

to that date that it was unique; Mr. Lincoln's responsibilities were considerable as he had charge of the operating department. In 1902 he returned to the Westinghouse Company in Pittsburgh and was in charge of the power division of the engineering department for six years. He was appointed general engineer for the company in 1910, holding that position until 1919. At that time he resigned from his position with the Westinghouse Company to join the firm of his older brother, the Lincoln Electric Company, as consulting engineer. From 1911 to 1915 he was head of the electrical school at the University of Pittsburgh, and in 1922 became director of the school of electrical engineering at Cornell University. He became professor emeritus in 1938, and in the same year became president of the Therm-Electric Meter Company. In 1902 he was the recipient of the John Scott Medal of the City of Philadelphia for his invention of the synchroscope. The honorary degree of doctor of engineering was conferred upon him in 1933 by Ohio State University. Professor Lincoln served the Institute as manager (1906–09), as vice-president (1909–11), and as president (1914–15). He was active on Institute committees, serving on the papers, and meeting and papers (now technical program) committees, on the executive, Sections, and law committees, and on many technical committees, including power stations, protective devices, transmission and distribution, electrical machinery, Standards, and instruments and measurements. He served on the board of award of the John Fritz Medal, and on the Edison and Lamme Medal committees. He was a member of the board of management of the World's Congress of Engineers, 1923–25, and was a member of several scientific and engineering societies in the United States.

Paul Milton Downing (A '98, M '08, F '42) executive vice-president of the Pacific Gas and Electric Company, San Francisco, Calif., died December 11, 1944. Mr. Downing was born in Newark, Mo., November 27, 1873, and was graduated from Stanford University in 1895 with the first graduating class. Before entering upon his lifetime association with the Pacific Gas and Electric Company, he was employed by several other power companies, the Tacoma (Wash.) Light and Power Company, the Market Street Railway Company, San Francisco, the Standard Consolidated Mining Company (three companies which later merged with the Pacific Gas and Electric Company), and by the Colusa Gas and Electric Company, the Bay Counties Power Company, and the California Gas and Electric Company. When the Pacific Gas and Electric Company was formed by merger in 1908, he became engineer of maintenance and operation. He was made chief engineer in 1917, vice-president in charge of electrical construction and operation in 1920, vice-president and general manager in 1929, and executive vice-president in 1943. One of his latest accomplishments in this position was the completion of Pit 5 hydroelectric station in Shasta County, Calif., the largest installation of its kind in that state. Mr. Downing was an AIEE vice-president from 1925 to 1927, a vice-president of the Edison Electric Institute, and a past president of the Pacific Coast Electrical Association.

Herbert Stead Sands (A '06, M '13) consulting engineer and president of the Denver Board of Water Commissioners, died December 13, 1944. He was born in Stamford, Conn., July 27, 1874, and was student engineer with the Edison General Electric Company from 1889 to 1894. He was superintendent for the Baltic (Conn.) Power Company from 1893 to 1899, for the Cripple Creek District Railway in 1899, and for La Bella Mill, Water, and Power Company, Goldfield, Colo., from 1899 to 1901. From 1901 to 1905 he was associated with the Seaton Mountain Electric Light and Power Company, Idaho Springs, Colo. Mr. Sands was manager of the industrial division of the Westinghouse Electric and Manufacturing Company, Denver, Colo., from 1905 until his retirement to private practice in 1927. Active in civic affairs, Mr. Sands was president of the Denver Chamber of Commerce from 1929 to 1932 and in 1932 was voted an honorary life membership in that body. He was a member of the board of directors of the Public Service Company of Colorado and president of the State Board of Engineering Examiners. He was a member of the Colorado Engineering Council and its president from 1925 to 1927. He was made an honorary member of the Colorado University chapter of Tau Beta Pi and received the degree of electrical engineer from that institution in 1926. He was a director of the Home Loan Bank of Topeka and a member of the Colorado Scientific Society.

Joseph Arthur Jeffery (M '20) vice-president of the Champion Spark Plug Company and general manager of its ceramic division in Detroit, Mich., died December 26, 1944. Doctor Jeffery, who was born in San Francisco, Calif., in 1873, was graduated from the University of California with a degree in dentistry in 1895. From 1897 to 1900 he was instructor in chemistry and metallurgy at the University of California. While he was practicing dental surgery in San Francisco, his interest in dental porcelains broadened to ceramics in general. Experiments with synthetic sillimanite led him to a search for natural deposits worthy of commercial exploitation. In 1918 he discovered such deposits in the Inyo range in California and thereupon founded the Jeffery-Dewitt Company and the Jeffery-Dewitt Insulator Company of which he became president. These companies were merged with the Champion Spark Plug Company in 1921. Doctor Jeffery also was president of the Champion Sillimanite, Inc., of California and Nevada, a subsidiary of the parent company. He was a member of the American Ceramic Society, the Electrochemical Society, the American Institute of Mining and Metallurgical Engineers, and the Detroit Engineering Society.

William Lawrence Tadlock (A '29, M '37) supervising electrical distribution engineer, Commonwealth and Southern Corporation, Birmingham, Ala., died November 27, 1944. Born in Talbott, Tenn., March 11, 1902, he was graduated from the Carnegie Institute of Technology with the degree of bachelor of science in electrical engineering in 1924. In 1924 and 1925 he worked on radio research for the General Electric Company, Schenectady, N. Y., and in 1925 established his own radio-broadcasting receiver service in Knoxville, Tenn. From 1926 to 1930 he was distribution engineer with what is now the Tennessee Public Service Company. In 1930 he joined the Allied Engineers, Inc., in Atlanta, Ga., which was later absorbed by the Commonwealth and Southern Corporation, and worked on the design and construction of underground distribution systems. In this position he planned expanded distribution systems for the cities of Nashville and Chattanooga, Tenn. He was employed as engineer in the Navy Yard expansion at Pearl Harbor in the Hawaiian Islands from 1934 to 1936. In 1936 he returned to the United States to become supervising engineer for the Commonwealth and Southern Corporation. Mr. Tadlock was author of the article, "Evaluation of Incompletely Diversified Loads," published in the November 1943 issue of *Electrical Engineering*.

Leon Walter Rosenthal (A '02, M '13, F '19) engineer, inventer, and patent soliciter, New York, N. Y., died January 8, 1945. Mr. Rosenthal was born August 9, 1880, in Marlin, Tex., and was graduated from Columbia University with the degree of electrical engineer in 1902. He was assistant to George H. Sever, consulting engineer, and professor of electrical engineering at Columbia University, New York, until 1903 when he joined the New York Central and Hudson River Railroad to work on the electrification of its New York zone. In 1909 he went to Guatemala to design and lay out an electric railway for that country. Returning to New York in 1910 he joined the patent-attorney firm of Pennie, Davis, Marvin, and Edmonds with which he remained until 1918 when he was retained by the Alien Property Custodian as patent counsel for the Bosch Magneto Company. In 1919 he became vice-president of the American Bosch Magneto Corporation, and in 1934 he opened a private patent practice. Mr. Rosenthal held a number of patents in his own right and was the author of several books, including "Calculation of Electrical Transmission Lines" and "Arnheim and Multiplex Slide Rules." He was a member of the Society of Automotive Engineers and the Radio Club of America.

Alf Hjort (M '21) chief engineer, George H. Flinn Corporation, New York, N. Y., died December 12, 1944. Born October 12, 1877, in Oslo, Norway, Mr. Hjort was graduated from the Technical College of Hanover, Germany. He worked in Berlin, Germany, in the testing department of the Bergman Electric Company in 1902 and in the calculating department of the General Electric Company in 1903. After coming to the United States he was employed by S. Pearson and Sons, contractors, on the Pennsylvania Railroad East River tunnels from 1904 to 1909. He was electrical engineer in charge of the New York City aqueduct for the Degnon Contracting Company from 1909 to 1911. In 1911 he joined the Flinn Corporation, then known as Booth and Flinn, Ltd., and in 1929 became chief engineer for the corporation. Throughout this association he worked on many tunnel and sewer projects in the New York area. Mr Hjort was a member of the American Society

of Municipal Engineers and the American Society of Military Engineers.

William Lord Bliss (A '94, F '17) consulting engineer, USL Battery Corporation, Niagara Falls, N. Y., died December 5, 1944. Mr. Bliss was born July 16, 1871, in Brooklyn, N. Y., and received the degree of bachelor of science in electrical engineering from the Polytechnic Institute of Brooklyn in 1891 and the degree of master of mechanical engineering from Cornell University in 1893. He developed his lifelong interest in carlighting apparatus during early employment with the Riker Electric Motor Company, Brooklyn, N. Y., in 1893 and with the Consolidated Gas Company, New York, N. Y. From 1897 to 1901 he engaged in private research on the subject and in 1901 he formed the Bliss Electric Car Lighting Company of New Jersey. When this company was consolidated into the United States Light and Heating Company, Mr. Bliss was made chief engineer, and he continued in that position with its successor the USL Battery Corporation. He retired to the position of consulting engineer in 1941. He was the holder of numerous patents.

Francis Wymond Hurlbert (A '04) retired electrical sales engineer of the International General Electric Company, New York, N. Y., died December 4, 1944. Born in Aurora, Ind., June 3, 1870, Mr. Hurlbert was graduated from Rose Polytechnic Institute in 1891 with the degree of bachelor of science in electrical engineering. His early career was concerned with railway engineering for the Detroit Street Railways; the Brush Electric Company, Cleveland, Ohio; and in the railway-engineering department of the General Electric Company, Schenectady, N. Y. In 1902 he entered the foreign department of the latter company and in this connection was sent to Mexico. Upon his return he entered the sales department and later was transferred to the New York, N. Y., office of the foreign department, which eventually became the International General Electric Company. In 1901 Mr. Hurlbert had charge of the General Electric Company exhibit at the Pan American Exposition in Buffalo, N. Y.

Leroy Coffin (A '37, M '41) electrical engineer, Bureau of Ships, Washington, D. C., died November 16, 1944. Born June 8, 1899, in Carlos City, Ind., Mr. Coffin was graduated from Purdue University with the degree of bachelor of science in electrical engineering in 1923. He was associated with the Allis-Chalmers Manufacturing Company, Milwaukee, Wis., from 1923 to 1941 as student engineer; special investigator on telephone problems; designer of induction motors, turboalternators, and other equipment; and writer of instruction books. From 1928 to 1934 he was instructor in the evening session of the Milwaukee Vocational School. In 1940 he was loaned to the Bureau of Ships where he was regarded as an outstanding authority on electric ship propulsion. He was one of the key figures in the repair of the battleships sunk or damaged at Pearl Harbor in 1941.

Theodore Schou (M '14) consulting engineer, Fairbanks, Morse, and Company, Beloit, Wis., died November 16, 1944. Born in Förde, Norway, on March 23, 1879, Mr. Schou was graduated from the Royal Academy of Kristiana, Norway, in 1897. He came to the United States in 1903 and in 1904 entered the employ of Westinghouse, Church, Kerr, and Company, New York, N. Y. Ensuing positions included designing engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., in 1911; professor at the State University of Iowa, Iowa City, in 1916; and chief engineer, the Ideal Electric and Manufacturing Company, Mansfield, Ohio, in 1920. He joined Fairbanks, Morse, and Company in 1928 as chief electrical engineer. Mr. Schou was the author of numerous articles for technical magazines.

Theodore Varney (A '05) an electrical engineer of New York, N. Y., died October 2, 1944. On January 27, 1875, Mr. Varney was born in Fort Leavenworth, Kans., and in 1894 he was graduated from the Massachusetts Institute of Technology. In 1901 he was with the Westinghouse Electric and Manufacturing Company, Pittsburgh, Pa.; in 1913 with the Commonwealth Electric and Supply Company, and in 1915 with the Aluminum Company of America, both of Pittsburgh. In 1928 Mr. Varney was a consulting engineer for Aluminum Ltd. of New York, N. Y., and in 1935 he went to Aluminum Ltd., of Montreal, Quebec, Canada. Mr. Varney returned to the United States in1939.

Thomas R. Crumley (A '19) president, Jersey Central Power and Light Company, Asbury Park, N. J., died October 5, 1944. Mr. Crumley was born in Wayne, Pa., on September 20, 1878. He began his career in 1901 in the testing and engineering department, General Electric Company, Schenectady, N. Y. He was engaged in transportation work from 1910 to 1915 as superintendent of motive power, Evansville (Ind.) Railways Company. In 1915 he became chief engineer for the Engineering and Management Corporation, New York, N. Y., and in 1921, president. Mr. Crumley became president of the Jersey Central Power and Light Company in 1928.

Frank A. Teach (A '24, M '29) relay engineer, Columbus and Southern Ohio Electric Company, Columbus, Ohio, died October 25, 1944. Born on August 8, 1892, in Pleasant Hill, Ohio, Mr. Teach was graduated in 1921 from Ohio State University and received the master of arts degree in 1938. During the first World War he was a lieutenant in the Signal Corps of the United States Army. In 1921 he was superintendent of construction for the State Highway Department of the State of Ohio and from 1923 to 1928 he was electrical engineer and inspector for the Department of Buildings, Columbus. Subsequently, Mr. Teach was with Gustave Hirsch, consulting engineer of Columbus, and the Columbus Railway, Power and Light Company. He joined the Columbus and Southern Ohio Electric Company in 1937. He was a member of the State Board of Registration of Professional Engineers and Surveyors.

Willard L. Newman (M '35) equipment cost engineer, long-lines department, American Telephone and Telegraph Company, New York, N. Y., died October 31, 1944. Mr. Newman was born in Blairstown, N. J., on April 8, 1888, and was a graduate of Lehigh University (1912). His entire professional career was spent in the long-lines department of the American Telephone and Telegraph Company, which he entered in 1912 in Buffalo, N. Y., where his work consisted of maintaining central-office telephone and telegraph equipment. After holding various other positions with the company, Mr. Newman was made equipment cost engineer in 1941.

Charles G. Atkins (A '01, M '21) consulting engineer, Chicago, Ill., died October 20, 1944. Born on February 16, 1865, in Tiffin, Ohio, Mr. Atkins was a graduate of the University of Michigan (1893). Following his graduation, Mr. Atkins became assistant to the chief engineer of tests and constructing work on roads, Westinghouse Electric and Manufacturing Company. In 1896 he entered the employ of the Chicago (Ill.) Edison Company in the engineering department. Mr. Atkins had been a consulting engineer since 1901. He was a member of the Western Society of Engineers.

MEMBERSHIP

Recommended for Transfer

The board of examiners, at its meeting on January 18, 1945, recommended the following members for transfer to the grade of membership indicated. Any objections to these transfers should be filed at once with the national secretary.

To Grade of Fellow

Angus, D. J., president and chief engr., Esterline-Angus Co., Indianapolis, Ind.

Bosch, L. L., chief, Equipment Production Branch, WPB, Washington, D. C.

Sah, A. P. T., president, National University of Amoy, Changting, Fukien, China; at present M.I.T.

3 to grade of Fellow

To Grade of Member

Arenberg, A. L., president, Luminator Inc., Chicago, Ill.

Batten, W. B., section engr., Westinghouse E. & M. Co., E. Pittsburgh, Pa.

Brown, A. D., district mgr., Allis-Chalmers Mfg. Co., Los Angeles, Calif.

Caswell, R. W., senior engr., Public Service Co. of Northern Illinois, Chicago, Ill.

Catherwood, T. E. D., chief electrician, Buffalo Ankerite Gold Mines, Ltd., So. Porcupine, Ont., Can.

Collins, R. K., district elec. engr., Westinghouse E. & M. Co., Los Angeles, Calif.

Cox, J. H., section engr., Westinghouse E. & M. Co., E. Pittsburgh, Pa.

Crippen, M. E., engr., U. S. Engineer Office, Little Rock, Ark.

Easley, G. J., design engr., Westinghouse E. & M. Co., E. Pittsburgh, Pa.

Herring, H. C., exchange engr., Southwestern Bell Tel. Co., Beaumont, Texas.

Hewitt, G. W., research engr., Westinghouse E. & M. Co., E. Pittsburgh, Pa.

Hollingshead, E. C., design engr., Westinghouse E. & M. Co., Sharon, Pa.

House, H. E., elec. engr., Aluminum Co. of America, Alcoa, Tenn.

Kelley, J. R., engr. of underground distribution, Dept. of Water and Power, Los Angeles, Calif.

Lieberkind, H. E., elec. engr. draftsman, West Penn Power Co., Pittsburgh, Pa.

Marshall, L. E., engr., Knoxville Elec. Pwr. & Water Board, Knoxville, Tenn.

Mentzer, R. D., test engr., Willamette Iron & Steel Co., Portland, Oreg.

Nichols, W. A., plant engr., Canadian Broadcasting Corp., Montreal, Can.

Nimmer, F. W., general distribution engr., Ohio Edison Co., Akron, Ohio

Oerman, H. W., underground engr., Public Service Co. of Northern Illinois, Chicago, Ill.

Pakala, W. E., design engr., Westinghouse E. & M. Co., E. Pittsburgh, Pa.

Parker, J. C., supervisor, Memphis Light, Gas & Water Div., Memphis, Tenn.

Pollard, E. I., design engr., Westinghouse E. & M. Co., E. Pittsburgh, Pa.

Schraneck, J. E., elec. engr., Westinghouse E. & M. Co., E. Pittsburgh, Pa.

Selfke, F. A., draftsman, West Penn Power Co., Pittsburgh, Pa.

Stewart, V. N., design engr., General Elec. Co., Philadelphia, Pa.

Straube, A. W., plant engr., Daugherty Refinery, Petrolia, Pa.
Sutton, G. E., transformer specialist, General Elec. Co., Philadelphia, Pa.
Thrasher, M. J., elec. engr., Texas Power & Light Co., Dallas, Texas.
Tinnerholm, R. F., mgr., switchgear div., General Elec. Co., Philadelphia, Pa.
Watson, P. R., asst. materials and processes engr., Curtiss-Wright Corp., St. Louis, Mo.
Woods, C. A., design engr., Westinghouse E. & M. Co., E. Pittsburgh, Pa.
Woodward, B. W., development engr., Remington Rand, Inc., Tonawanda, N. Y.

33 to grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. Any member objection to the election of any of these candidates should so inform the national secretary before February 28, 1945, or April 30, 1945, if the applicant resides outside of the United States or Canada.

To Grade of Member

Anspach, R. J., Amer. Tel. & Tel. Co., New York, N. Y.
Buehler, C. M., Taylor Inst. Co., Rochester, N. Y.
Davis, H. P., Ohio Bell Tel. Co., Akron, Ohio.
Dellever, O. J., Expediters, Ltd., San Francisco, Calif.
Deschenitz, J. Sou. Bell Tel. & Tel. Co., Atlanta, Ga.
Deloney, H. L., La. Pr. & Lt. Co., New Orleans, La.
Doerr, C. G., Northern Ind. Pub. Serv. Co., Plymouth, Ind.
Douglas, P. W., Chrysler Corp., Chicago, Ill.
Draper, R. O., Gen. Cable Corp., Perth Amboy, N. J.
Duke, C. A., Tenn. Valley Auth., Chattanooga, Tenn.
Friar, E. M., Carolina Tel. & Tel. Co., Tarboro, N. C.
Goodell, S. E., Commonwealth Edison Co., Chicago, Ill.
Hanley, E. L. (Reelection), Wis. Tel. Co., Milwaukee, Wis.
Hayes, J. H., Thirlwell, Henderson, Marine Elec. Co., Evansville, Ind.
Hemperly, J. H., Willamette Iron & Steel Corp., Portland, Oreg.
Henry, L. W., Shell Oil Co., Inc., Wood River, Ill.
Kerstein, C. I., Rosenblatt & Hunt, Inc., Charleston, W. Va.
Larson, N. G. (Reelection), Commonwealth Edison Co., Chicago, Ill.
Lehr, C. N., Monitor Cont. Co., Baltimore, Md.
Lewis, R. P., Westinghouse Elec. & Mfg. Co., Boston, Mass.
Matthews, C. L. (Reelection), Brockway Land & Water Co., Brockway, Calif.
McElwee, J. M. (Reelection), Chicago Dist. Elec. Gen. Corp., Hammond, Ind.
Miller, H. E., E. I. du Pont de Nemours & Co., Wilmington, Del.
Parillo, L., Hercules Powder Co., Wilmington, Del.
Preston, A. S., Tenn. Eastman Corp., Oak Ridge, Tenn.
Priest, G. A. (Reelection), General Elec. Co., Syracuse, N. Y.
Randall, H. J., Dunlop Rubber Co. Ltd., Birmingham, England.
Riley, L. G. (Reelection), Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
Shaw, W. R., Major, G.H.Q. (I), New Delhi, India.
Tegel, J. P. (Reelection), Commonwealth Edison Co., Chicago, Ill.
Thuem, C. H. (Reelection), George G. Sharp, New York, N. Y.
Watson, G. O., Lloyd's Reg. of Shipping, London, England.
Williamson, G. L., Gibson Elec. Co., Pittsburgh, Pa.

33 to grade of Member

To Grade of Associate

United States and Canada

1. North Eastern

Alimansky, M. I. (Reelection), Gen. Elec. Co., Pittsfield, Mass.
Bigsby, O. S. (Reelection), Central N. Y. Pr. Corp., Syracuse, N. Y.
Blakeslee, G. T., 1st Lieut., U. S. Army, Horseheads, N. Y.
Boughter, C. L., N. Y. State Elec. & Gas Corp., Binghamton, N. Y.
Brighman, J., Gen. Elec. Co., Schenectady, N. Y.
Burns, F. J., Jr., Eastman Kodak Co., Rochester, N. Y.
Corea, E. V., U. S. Naval Dry Dock, South Boston, Mass.
Daw, A. H., Buffalo Niag. Elec. Corp., Buffalo, N. Y.
Holt, F. H. (Reelection), Gen. Elec. Co., Schenectady, N. Y.
Humpage, H. A., Fed. Elec. Prod. Co., Inc., Hartford, Conn.
Hylwa, L., Sylvania Elec. Prod., Inc., Danvers, Mass.
Johnson, R. R., Gen. Elec. Co., Schenectady, N. Y.
King, C. W. (Reelection), Allis-Chalmers Mfg. Co., Buffalo, N. Y.
Librock, G. E., Remington-Rand, Inc., Tonawanda, N. Y.
Myers, M. G., Jr., Westinghouse Elec. & Mfg. Co., Boston, Mass.
Sams, F. W., American Steel & Wire Co., Worcester, Mass.
Simpson, R. E., Westinghouse Elec. & Mfg. Co., Boston, Mass.
Stanton, W. H., N. Y. State Elec. & Gas Corp., Ithaca, N. Y.
Stiehl, P. L. E., Lewis Engg. Co., Naugatuck, Conn.
Stockwell, S. W., Davis Transformer Co., Concord, N. H.
Switzer, D. C., N. Y. State Elec. & Gas Corp., Geneva, N. Y.

2. Middle Eastern

Ash, W. J., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
Bean, W. E., Westinghouse Elec. & Mfg. Co., Huntington, W. Va.
Bovier, R. F., Northern Penna. Pr. Co., Towanda, Pa.
Canning, R., Pittsburgh Plate Glass Co., Creighton, Pa.
Chambers, W. L., Charleston Elec. Supply Co., Charleston, W. Va.
Dawson, G. G., Westinghouse Elec. & Mfg. Co., Charleston, W. Va.
Foschia, L. J., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
Givner, S., Allis-Chalmers Mfg. Co., Norwood, Ohio.
Gordon, M. K., Jr. (Reelection), Bendix Avia. Corp., Philadelphia, Pa.
Haring, R., N. Y. Shipbldg. Corp., Camden, N. J.
Hufton, R. V., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
Jacoby, W., I.T.E. Circuit Breaker Co., Philadelphia, Pa.
Kent, H. B., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
Lindsey, H. L., Charleston Elec. Supply Co., Charleston, W. Va.
McCabe, E. F., Lieut., U. S. Army Air Forces, Dayton, Ohio.
McCloskey, W. J., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
Melhorn, N. R., Jr., Radio Corp. of America, Lancaster, Pa.
Mills, C. E., U. S. Rubber Co., Institute, W. Va.
Nevin, R. A., Leland Elec. Co., Dayton, Ohio.
Noel, E. B., General Elec. Co., Cleveland, Ohio.
Ormsbee, L. A., Westinghouse Elec. & Mfg. Co., East Pittsburgh, Pa.
Ransford, H. E. (Reelection), H. E. Ransford Co., Pittsburgh, Pa.
Richards, H. M., Virginian Elec., Inc., Charleston, W. Va.
Riedel, G. B., Scranton Elec. Co., Scranton, Pa.
Shipka, A. F., Leece-Neville Co., Cleveland, Ohio.
Spackman, A. L., British Overseas Airways, Baltimore, Md.
Timpe, N. B., Phila. Elec. Co., Philadelphia, Pa.
Vance, W. W., Toledo Scale Co., Toledo, Ohio.
Vogt, S. H., Westinghouse Elec. & Mfg. Co., Lima, Ohio
Williams, M., Westinghouse Elec. & Mfg. Co., Sharon, Pa.
Wise, B. L. (Reelection), Fed. Mach. & Welder Co., Warren, Ohio.

3. New York City

Grandin, F., Alan-Wood Steel Co., Ringwood, N. J.
Hawes, C. W., Fed. Tel. & Radio Corp., Newark, N. J.
Hoyer, E. W., Weston Elec. Inst. Corp., Newark, N. J.
Johnson, C. W., Philco Corp., New York, N. Y.
Kadlets, J. A., Gen. Elec. Co., Schenectady, N. Y.
Morch, W. J., Ebasco Services, Inc., New York, N. Y.
Nielsen, C. L., Ebasco Services, Inc., New York, N. Y.
Rudi, W. J., U. S. Navy, New York, N. Y.
Terwilliger, C. F., Gen. Elec. Co., Bloomfield, N. J.
Wappler, D., Pub. Serv. Elec. & Gas Co., Newark, N. J.

4. Southern

Axelsson, R. (Reelection), Fraser-Brace Engg. Co., Inc., Camden, Ark.
Baugh, F. F., Watt. Elec. Coil Co., Pineville, Ky.
Bryant, C. R., Sr., Bryant Elec. Repair Co., Inc., Gastonia, N. C.
Davis, R. K., U. S. Maritime Com., Wilmington, N. C.
Donadieu, F. A., La. Pr. & Lt. Co., New Orleans, La.
Hanley, R. J., U. S. Army, Robbins Field, Ga.
Harris, J. N., Tenn. Valley Auth., Knoxville, Tenn.
Hebert, H., Hebert Bros., Plaquemine, La.
Jones, C. T., South-Eastern Underwriters Assoc., Atlanta, Ga.
Kinard, A. R., U. S. Navy Yard, Charleston, S. C.
Kline, K. H., Tenn. Eastman Corp., Oak Ridge, Tenn.
Kunkles, M. V., Jr., U. S. Maritime Com., Wilmington, N. C.
Sharp, J. D., Jr., General Elec. Co., Atlanta, Ga.
Smith, C. L., Jr., U. S. Navy Yard, Charleston, S. C.
Voigt, E. E. (Reelection), Box 557, Summerville, S. C.
Wallace, C. M., Duke Pr. Co., Gastonia, N. C.

5. Great Lakes

Armstrong, F. C., Pub. Serv. Co. of Northern Ill., Joliet, Ill.
Bard, R. L., Commonwealth Edison Co., Chicago, Ill.
Booth, W. L., U. S. Navy, Chicago, Ill.
Brown, W. H., Keystone Steel & Wire Co., Peoria, Ill.
Bullard, H. M., Commonwealth Edison Co., Chicago, Ill.
Elliott, M. F., Pub. Serv. Co. of Northern Ill., Harvey, Ill.
Ely, O. G., Kingsbury Ord. Plant, La Porte, Ind.
Foulkes, H. J., Pub. Serv. Co. of Northern Ill., Streator, Ill.
Horkay, T. E., Central Ill. Elec. & Gas Co., Rockford, Ill.
Jeswick, M. J., Gen. Elec. Co., Chicago, Ill.
Kalm, A. V. (Reelection), Commonwealth Edison Co., Chicago, Ill.
Kartalia, M. P., Square D Co., Milwaukee, Wis.
Lauritsen, C. N. (Reelection), Pub. Serv. Co. of Northern Ill., Joliet, Ill.
Leinberger, F. H., Square D Co., Milwaukee, Wis.
Linn, G. J. (Reelection), Commonwealth Edison Co., Chicago, Ill.
Mekelburg, L. J., Square D Co., Milwaukee, Wis.
Osborne, R. H., Pub. Serv. Co. of Northern Ill., Joliet, Ill.
Phinney, L. W., Control Corp., Minneapolis, Minn.
Rood, G., Cutler-Hammer, Inc., Milwaukee, Wis.
Roth, P. H., Commonwealth Edison Co., Chicago, Ill.
Sherwood, B. C. (Reelection), Commonwealth Edison Co., Chicago, Ill.
Strai, B., Pub. Serv. Co. of Northern Ill., Chicago, Ill.
Sickel, S. J., Northwestern Pub. Serv. Co., Huron, S. Dak.
Thompson, M. J., Ind. & Mich. Elec. Co., South Bend, Ind.
Weaver, J. W., U. S. Maritime Com., Chicago, Ill.
Wheeman, T. R., Louis Allis Co., Milwaukee, Wis.

6. North Central

James, L. S. (Reelection), Pub. Serv. Co. of Colo., Boulder, Colo.
Stromquist, T. A., U. S. Bur. of Reclamation, Denver, Colo.

7. South West

Brill, G. F., Gulf States Util. Co., Beaumont, Texas.
Ellis, D. S., Southern Pac. R.R., Houston, Texas.
Graham, O. W., Texas Co., Houston, Texas.
Hickerson, H. B., Boeing Airplane Co., Wichita, Kans.
Sheets, D. H., Line Material Co. St. Louis, Mo.
Smith, F. D., Dallas Pr. & Lt. Co., Dallas, Texas.
Summers, O. V., Texas Pipe Line Co., Houston, Texas.

8. Pacific

Bell, R. L., Westinghouse Elec. & Mfg. Co., San Francisco, Calif.
Bowen, F. A., Westinghouse Elec. & Mfg. Co., Los Angeles, Calif.
Coombs, J. C., U. S. Engineers, Sacramento, Calif.
Elmore, J., Arden Farms Co., Los Angeles, Calif.
Freitas, E. A., Northrop Aircraft, Inc., Hawthorne, Calif.
Ginochio, F., Pacific Gas & Elec. Co., Sacramento, Calif.
Harding, J. G., Pacific Gas & Elec. Co., San Francisco, Calif.
Hausler, E. H. (Reelection), Westinghouse Elec. & Mfg. Co., San Francisco, Calif.
Hersam, E. C. (Reelection), Pacific Gas & Elec. Co., San Mateo, Calif.
Leithold, A. A., Food Mchry. Corp., Riverside, Calif.
McGinty, E. A. (Reelection), Pacific Gas & Elec. Co., Sacramento, Calif.
Mitchell, F. C., Kern Mutual Tel. Co., Taft, Calif.
Plesset, E. H., Douglas Aircraft Co., Inc., Santa Monica, Calif.
Rees, L. J., Fed. Pr. Com., San Francisco, Calif.
Sargent, W. S., Los Angeles Water & Pr. Dept., Los Angeles, Calif.
Steere, S. H., Southern Calif. Tel. Co., Los Angeles, Calif.
Swengel, F. M., Goodyear Aircraft Corp., Litchfield Park, Ariz.
Van Antwerp, E. D., Allis-Chalmers Mfg. Co., Los Angeles, Calif.
Whitehead, S. K., Southern Calif. Tel. Co., Los Angeles, Calif.
Whiteley, E., Pacific Gas & Elec. Co., San Francisco, Calif.
Wolbert, H. L., Southern Calif. Tel. Co., Los Angeles, Calif.
Young, F. L. (Reelection), Southern Calif. Tel. Co., Los Angeles, Calif.

9. North West

Aldrich, K. B. (Reelection), Bonneville Pr. Adm., Portland, Oreg.
Aust, G. E., Bonneville Pr. Adm., Vancouver, Wash.
Brittain, V. M., Willamette Iron & Steel Corp., Portland, Oreg.
Carlson, J. V., Puget Sound Pr. & Lt. Co., Seattle, Wash.
Cooper, C. C., Gen. Elec. Co., Portland, Oreg.
Gadeholt, B., N. W. Elec. Co. & Pacific Pr. & Lt. Co., Portland, Oreg.
Gill, J. W., Puget Sound Bridge & Dredg. Co., Seattle, Wash.
Heller, C. F., U. S. Navy, Portland, Oreg.
Houston, C. M., Bonneville Pr. Adm., Vancouver, Wash.
Kuder, A. S. (Reelection), Washington Water Pr. Co., Spokane, Wash.
Meiggs, R. F., Willamette Iron & Steel Corp., Portland, Oreg.
Pigrott, H. P., Montana Pr. Co., Great Falls, Mont.
Seat, A. W., Puget Sound Pr. & Lt. Co., Seattle, Wash.
Winters, B., Gen. Elec. Co., Seattle, Wash.

10. Canada

Dobesch, R. R., Elec. Sub-Lieut., R.C.N.V.R., Halifax, N. S., Can.
McCaslin, W. O., Mercury Mills, Hamilton, Ont. Can.
Patterson, J. G., Canadian Comstock Co. Ltd., Red Rock, Ont., Can.
Taylor, L. J., Can. Natl. Carbon Co., Ltd., Toronto, Ont., Can.

Elsewhere

Abreu, C. S. (Reelection), Cia. Matogrossense de Eletricidade, Brazil, Sao Paulo, S. A.
Aillaud, G. A., Gen. Motors de Mex., Mexico, D. F., Mex.
Darton, R. V., Johnson & Phillips, Ltd., London, England.
Garver, R. J., Royal Aircraft Estab., Farnborough, England.
Wong, S. M., Metropolitan-Vickers Elec. Co., Ltd., Manchester, England.

Total to grade of Associate
United States and Canada, 153
Elsewhere, 6

OF CURRENT INTEREST

Bureau of Ships Creates Electronics Division

With electronic devices assuming a more important place in the fields of naval communication, navigation, ordnance, gunnery, and tactics, and in the general battle efficiency of the Navy's airplanes and ships, the Bureau of Ships has broadened the scope of its older radio division and renamed it the electronics division. Captain J. B. Dow, who has been responsible for the design, production, and installation of the Navy's electronic equipment for several years, has been appointed director of electronics.

Among the division's personnel of 1,200 are numbered some of the foremost electronic authorities and engineers in the country. The research organizations of government and industry have fully collaborated with the division's engineers in producing radio, radar, and sonar equipment to secure its primary objective of maintaining a technical superiority over enemy equipment. Commenting on the divisions' work, Captain Dow recently estimated "the research work in the electronic field started before the war and carried on at an accelerated rate since hostilities commenced has resulted in advancing the electronic art by at least ten years."

Signal Corps Institutes Relay Radio in France

A system of very high-frequency radio relay equipment has been introduced in France by the United States Army Signal Corps as an answer to the communications problem which arises when the stringing of wire cannot keep pace with the speed of the campaign.

This radio relay system consists of stations 25 to 100 miles apart, each beamed on the next. Police scout-car equipment which had been procured for expected police communications requirements in North Africa was found to be very well suited for radio relay systems. After the system was tested in North Africa, it was developed in the United States and England.

The actual combat-line communications are built around radio. In addition to the individual radio networks which each field unit has, every tank has a radio, and a certain number of infantrymen from each company are equipped with voice pack sets. For communication with the United States, a high-powered multichannel 40-kw Army transmitter which took 25 days to assemble has been installed in France.

This Army radio station, with its $2,000,000 worth of equipment, operates from batteries of radio and landline teletype machines and sends out approximately 400,000 words a day. Direct hookups with Washington, London, the Army world-wide radio communications system including Africa and Italy, and Army headquarters on the continent, make possible the transmission of impulses along supply lines over 4,000 miles long.

Homing Pigeons' Reactions to Radio Waves Tested

Support for the belief that radio waves affect the instincts of homing pigeons has been supplied by a recent series of tests made by the United States Army Signal Corps. These tests apparently prove that radio transmission confuses the birds and retards them in fulfilling their flying missions.

Three successive tests were made with three different groups consisting of ten birds each, all of similar type and training. The birds were taken to a loft about ten miles from their home lofts. In each test five birds were released while the radio station was transmitting and the second five were liberated with the station silenced. Those birds released while the station was transmitting seemed completely bewildered. They circled erratically, very close to the station, for 15 or 20 minutes, then took off uncertainly for their lofts, requiring a total of 42 to 52 minutes to complete the 10-mile flight. Those freed while the station was silent made the usual brief circling, then took off promptly for the home loft with no confusion, covering the distance in 18 to 21 minutes. All birds flew under practically identical conditions of wind and weather.

The results of all three tests were virtually the same. However, the Signal Corps expects to test many more pigeons before the evidence can be accepted as conclusive.

Shortage of Electricity in Holland. An order issued by the authorities in the city of s'-Hertogenbosch limits the use of electric current to one 25-watt lamp for six hours each day, thus illustrating the shortage of electricity in Holland's liberated area. Under this condition, if there are two families in one home, one 15-watt and one 9-watt lamp may be used, or, if three families are living in the same house, three nine-watt lamps. In addition, the use of electric heaters and irons, vacuum cleaners, and washing machines is prohibited.

INDUSTRY . . . . .

Three Turbines Scheduled for Mexican Power Plant

With the first turbine already installed and in operation, work on the second of three turbines destined for a Mexican hydroelectric power plant is now in process. These turbines will operate with the highest "head" for this type unit in the western hemisphere, according to Ralph Kelly, president of the Baldwin Locomotive Works, the manufacturer. They are part of the Ixtapantongo Development of the Comision Federal de Electricidad, located on the Tilostoc River, about 100 miles southwest of Mexico City, and will furnish power through the Mexican Light and Power Company. Each turbine is to supply 39,000 horsepower under a head of 1,028 feet, and the total additional power generated will take Mexico City off present power rationing which limits citizens and industries to power for only eight of each 24 hours.

The unit is of the vertical-shaft Francis type provided with a butterfly valve and a Pelton relief valve to prevent pressure rises for load rejection. As compared with the Tennessee Valley Authority development on the Tennessee River between Knoxville and Chattanooga, the power developed is almost the same, but the Mexican turbines require only 372 cubic feet of water as against the 7,930 cubic feet for the TVA turbines, and the weight of the new turbine unit is only 260,000 pounds, a fraction of the weight of the larger unit. The new turbines are fed by water from a diversion dam built at a high level of the Tilostoc River.

New Ceramic Insulation Developed From Zircon

In order to cope with the shortage of electrical insulators for ultrahigh-frequency equipment, a new ceramic insulation known as zircon porcelain has been developed by the Westinghouse Electric and Manufacturing Company.

High-voltage porcelains and similar solid insulations have undesirably high energy losses when subjected to voltages in megacycle bands and the production of the ceramic insulation, steatite porcelain, has been limited by the lack of usable talc, one of its ingredients, and by the stringent conditions imposed on its processing.

The supply of mineral zircon is abundant, as it is found in the sands of beaches in many parts of the world, including Florida, India, Brazil, and Australia, and is a common constituent of many igneous rocks. The resultant zircon porcelain, which can be processed readily with standard equipment, is said to surpass other insulations in tensile strength, compressive strength, transverse strength, and ability to withstand moisture and heat shock.

POSTWAR . . . . .

FCC Releases Proposals for Frequency Allocation

Preliminary proposals of the Federal Communications Commission for dividing the postwar radio spectrum from 25,000 to 30,000,000 kilocycles among the two numerous applicants for spectrum space are contained in a report recently issued by the Commission.

Since the proposed allocations, based on public hearing held last fall, are only tentative, oral argument on their soundness and sufficiency will be heard by the Commission commencing on February 14, 1945.

Heated Clothing Tested on Copper Man

Five feet $10^1/_2$ inches tall with a copper "skin" $^1/_{16}$ of an inch thick, this copper man assembled according to dimensions furnished by the United States Army to the General Electric Company, Schenectady, N. Y., relieves human volunteers from suffering low temperatures during tests of electrically heated clothing and casualty blankets for the Armed Forces. A complicated system of electric wires connected to separate areas of the copper head, torso, feet, and hands enables reproduction of the inconstant temperature of the human body. The amount of heat-generating energy to each of the 15 areas of the copper body can be controlled separately and the temperature can range from subnormal to above normal. Aviators and bomber crews now can be comfortably and safely clad without subjecting human experimenters to the discomforts of high-altitude and low-temperature chambers

Aside from newcomers to the radio spectrums, the most notable changes in the present groupings are the removal of frequency modulation from 42–50 to 84–102 megacycles and the contraction of commercial television from 18 channels six megacycles wide at intervals from 50 to 294 megacycles to six channels six megacycles wide at intervals from 44 to 84 megacycles and an extra six channels from 180 to 216 megacycles. However space for television experimentation with color pictures and higher-definition monochromes also is allotted between 480 and 920 megacycles in the ultrahigh-frequency range.

The frequency-modulation broadcasting position is shifted on the grounds that skywave interference in the lower region would be severe enough to impair the utility of frequency modulation to the extent of retarding its full development. At this point the Commission deviates from the Radio Technical Planning Board recommendation, with the latter committed to the lower band of channels. Twenty of the 90 channels assigned to frequency modulation will be reserved for noncommercial educational use. Five such stations are now in use, eight additional applications are on file, and a widespread interest and support for this proposal has been expressed by educational institutions, according to the report. Opponents of this change of position for frequency modulation argue that existing transmitters must be remodeled and that most receiver sets will be outmoded, since only a few can be converted. However, the Commission contends that, even without a new spectrum allotment, normal progress expected after the war will bring this about. The change is not contemplated, it adds, until sets which can tune in on the new wave lengths are generally available.

Television was one of the most controversial questions discussed at the hearings, the report states. Many witnesses demanded that it be moved altogether into the ultrahigh-frequency range, and others objected to the reduction in the total amount of space granted. The Commission wished to keep television within the lower cycles, until receiver sets for the higher ranges were perfected and ready for general distribution.

Heavy demands of the aviation industry for radio channels above 25 megacycles in the postwar period are allowed by the Commission almost exactly as specified. In this connection, the importance of aviation to transportation and economic prosperity and the dependence of aviation upon radio for safety are emphasized.

Increased numbers of channels are suggested for amateur radio operation, police radio, fire-department use, and for miscellaneous emergency services. Channels for anticipated expansion of radio communication in business and between private citizens, for linking up isolated communities with telephone service, for industrial and medical service, and for general mobile traffic service also are set aside. The railroads are given a number of channels on their plea that radio will be a contribution to their greater postwar safety.

The Commission's report thanked the Radio Technical Planning Board for its aid, stating that most of that body's recommendations were embodied in the report. No dissenting report was filed by any of the Commissioners, because the report is not intended to represent the Commission's final decisions.

RMA Estimates Postwar Employment in Industry

The radio industry will provide postwar employment for about 68.6 per cent more men and women than its prewar employment, according to a recent survey made by the Radio Manufacturers Association. The employment total of the industry is expected to decrease only 39.8 per cent after a return to peacetime production because of the demand for radios to replace worn-out sets, as well as the anticipated postwar popularity of frequency-modulation receivers and, a little later, television. This will mean that 28.5 per cent of the present industry employees will be forced to seek work in another field, because of war contract cutbacks and the return of former employees now in the armed services. However, many of those now employed, such as housewives, will not continue working after the war.

The RMA survey was one of the first postwar employment studies made by a large industry. It includes figures from 202 companies, representing 64.9 per cent of the industry. This covers the largest and virtually all substantial manufacturers and represents about 80 per cent of industry employees.

EDUCATION . . .

University of Maryland to Have Aeronautical School

Plans for establishment of a college of aeronautical education and research and endowment of the Glenn L. Martin Aeronautical Research Foundation have been announced by the University of Maryland on receipt of an initial gift of $1,700,000 from The Glenn L. Martin Company for this purpose.

Of the total amount, $1,500,000 plus $750,000 in State funds, will be allotted for the construction of facilities. The remaining $200,000 will be used at the outset to endow the Research Foundation.

Gift to Brown University. Expansion of the engineering laboratory facilities by the addition of a second floor to the Engineering Laboratory Building at Brown University will be accomplished as the result of a gift of $30,000 from the Hammel-Dahl Company, Providence, R. I. The gift was prompted by the co-operation between research workers at the University and the company in the performance of the latter's Government contracts during 1944.

JOINT ACTIVITIES

United Engineering Trustees, Inc., Issues Report; Elects Officers

A resurgence of the planning for future adequate housing for the engineering societies which was suspended by the advent of the war is forecast for the coming year in the annual report of UET, Inc., submitted to the AIEE and the other participating societies by F. Malcolm Farmer, president.

With the growth of society membership from about 9,000 in 1907 to its present 70,000, finding even sufficient headquarters space in the Engineering Societies Building rapidly is becoming a problem, and the inadequacy of the building for meetings is evidenced in the accepted practice of holding annual meetings in more commodious hotels. According to the report there is urgent need for decisions on such questions as:

1. Should the present Engineering Societies Building be modernized and made adequate for the exclusive occupancy of the Founder Societies.

2. Should a new building be erected on a new site to be occupied only by the Founder Societies.

3. Should a large building project to constitute an engineering center be undertaken on the present site, or some other suitable site; one which would provide headquarters and ample meeting facilities for all engineering societies as well as the Founder Societies.

4. Should the latter project be further expanded to include the Engineers' Club and offices for practicing engineers and engineering concerns, that is, revive the plan seriously studied in 1931 by a joint committee of the UET and the Engineers' Club?

Though meeting facilities will be improved slightly for the immediate future by the return to their original purpose of several meeting halls which had been converted temporarily into emergency offices for the war projects of one society, this offers no lasting solution to the space problem.

All available office space in the building now is occupied by strictly engineering organizations, with about 61 per cent of the space allotted to offices. During the past year meeting halls have been used for military instruction and meetings, and the library has been in daily use by the War Department and members of the Armed Forces making special studies. Replacement of broken waterpipes and new risers in the wiring system were the only major repairs made during the year to the building which otherwise is in excellent physical condition. Both fire and extended coverage insurance is carried and war damage insurance has been renewed automatically so that all contingencies can be met, the report states in covering the subject of the general utility of the building.

Increased revenue from meeting-hall rentals and reduction to token payments of $500 of the interest payments formerly made to the Founder Societies have left the UET with a credit balance of $286.70 for the year, compared with a debit balance of $1,615.24 for the previous year. This has been effected despite increased labor costs and emergency repairs. Though a rise in building labor costs is expected, it is hoped that meeting-hall rental and space-assessment income will offset the rise. The report adds that repairs now are charged against current income rather than the building-depreciation reserve fund, thus allowing the latter to accumulate against the diminishing value of the Societies building at the maximum rate obtainable from the yearly allocation of $20,000. The book value of investments at the close of the fiscal year was $1,503,175.93 and the market value was $1,524,293.64, or approximately 101½ per cent of book value, against last year's market value which was 102 per cent of book value.

In order to clarify the prevalent confusion about the division of its income between building expenses and other activities, the UET has broken down its expenses into approximated percentages. Of the total assessments paid by the Founder and associate societies, about 16 per cent goes to the replacement of building equipment (depreciation fund) 62 per cent toward operating the Engineering Societies Building, and 22 per cent to operating UET, Inc., as a corporation, which is the custodian of the joint Founder Society funds and an agency through which certain joint activities of the Founder Societies are carried on.

It is hoped, the report concludes, that the almost certain expansion of postwar cooperation among engineering societies will be reflected in an increased use of UET in the interest of economy of overhead expenses and a minimum of duplicated effort.

In addition to the executive officers previously announced (*EE, Dec '44, p 458*) the following were elected to the board of trustees for terms expiring in 1948: R. E. Dougherty, Ralph B. Williams, J. Schuyler Casey, and Everett S. Lee.

Members of the finance committee are:

George L. Knight, *chairman* — Albert Roberts
J. Schuyler Casey — Arthur S. Tuttle
C. R. Jones — R. B. Williams
F. M. Farmer, *ex officio*

Members of the real estate committee are:

A. L. Queneau, *chairman* — R. E. Dougherty
J. P. H. Perry — Henry A. Lardner
Everett S. Lee — F. M. Farmer, *ex officio*

Members of the executive committee are:

F. Malcolm Farmer, *chairman* — A. L. Queneau
Arthur S. Tuttle — George L. Knight
Albert Roberts

Engineering Foundation Summarizes Year's Research; Elects Officers

Officers elected for the year 1944–45 at the recent annual meeting of the Engineering Foundation, joint research agency of the Founder Societies, are:

Chairman, A. L. Queneau

Vice-chairman, A. B. Kinzel

Director, Edwin H. Colpitts

Secretary, John H. R. Arms

Members of the executive committee in addition to the chairman, vice-chairman, and secretary of the Foundation are: J. Schuyler Casey, R. H. Chambers, R. E. Dougherty.

Members of the Foundation board for 1944–45 with the dates of expiration of their terms are:

Trustees elected by the board of trustees of UET, Inc.
A. L. Queneau, AIME, 1945
J. Schuyler Casey, ASME, 1947
C. R. Jones, AIEE, 1947
R. E. Dougherty, ASCE, 1948
President, UET, Inc., ex officio
F. Malcolm Farmer,
Members-at-large
O. E. Buckley, AIEE, 1946
R. H. Chambers, ASCE, 1947
A. B. Kinzel, AIME, 1947
Members nominated by Founder Societies
F. F. Colcord, AIME, 1946
E. M. T. Ryder, ASCE, 1946
F. Malcolm Farmer, AIEE, 1947
Joel D. Justin, ASCE, 1947
A. A. Potter, ASME, 1947
L. W. Chubb, AIEE, 1948
E. A. Prentis, Jr., AIME, 1948
W. Trinks, ASME, 1948

Members of the research procedure committee are:

L. W. Chubb, *chairman*, Foundation representative
E. A. Prentis, Jr., Foundation representative
H. E. Wessman, ASCE
W. M. Peirce, AIME
W. Trinks, ASME
W. A. Lewis, AIEE

Chairman Queneau was appointed to represent the Foundation on the executive board of the National Research Council.

The personnel of other committees as appointed or reappointed at this meeting follows:

Iron Alloys Committee

Jerome Strauss, *chairman*; vice-president, Vanadium Corporation of America, New York, N. Y., representing American Society for Testing Materials.

Lyman J. Briggs, director, National Bureau of Standards, represented by J. G. Thompson, senior metallurgist, National Bureau of Standards, Washington, D. C.

James H. Critchett, vice-president, Union Carbide and Carbon Research Laboratories, New York, N. Y., representing American Electrochemical Society.

John Johnston, director of research, United States Steel Corporation, Kearny, N. J., representing American Iron and Steel Institute.

James T. Mackenzie, chief metallurgist, American Cast Iron Pipe Company, Birmingham, Ala., representing American Foundrymen's Association.

R. R. Sayers, director, United States Bureau of Mines, represented by R. S. Dean, assistant director, United States Bureau of Mines, Washington, D. C.

Bradley Stoughton, professor emeritus, Lehigh University, Bethlehem, Pa., representing American Society for Testing Materials.

Wilfred Sykes, president, Inland Steel Company, Chicago, Ill., member-at-large.

T. H. Wickenden, assistant manager, development and research division, International Nickel Company, Inc., New York, N. Y., representing Society of Automotive Engineers.

Frank T. Sisco, *consultant*, assistant secretary, AIME, New York, N. Y.

Welding Research Council

C. A. Adams, *chairman*; E. G. Budd Manufacturing Company, Philadelphia, Pa.

A. S. Albright, acting chief of research, Detroit Edison Company, Detroit, Mich.

David Arnott, vice-president, American Bureau of Shipping, New York, N. Y.

H. C. Boardman, *vice-chairman*; director of research, Chicago (Ill.) Bridge and Iron Company.

Everett Chapman, P. O. Box 387, Coatesville, Pa.

J. H. Critchett, vice-president, Union Carbide and Carbon Research Laboratories, New York, N. Y.

J. J. Crowe, assistant to vice-president and operating manager, Air Reduction Sales Company, New York, N. Y.

C. E. Davis, vice-president, Alan Wood Steel Company,

Conshohocken, Pa., representing the American Iron and Steel Institute.

C. L. Ekergian, chief engineer, Budd Wheel Company, Detroit, Mich.

A. J. Ely, mechanical engineer, Standard Oil Development, Elizabeth, N. J.

F. H. Frankland, 271 Madison Avenue, New York, N. Y.

T. S. Fuller, works laboratory, General Electric Company, Schenectady, N. Y.

Isaac Harter, vice-president, Babcock and Wilcox Company, Barberton, Ohio.

D. S. Jacobus, advisory engineer, 93 Harrison Avenue, Montclair, N. J.

G. F. Jenks, 232 Avondale Avenue, Los Angeles, Calif.

Carl M. Loeb, Jr., vice-president, Climax Molybdenum Company, New York, N. Y.

Arthur E. Pew, vice-president, Sun Oil Company, Philadelphia, Pa.

G. A. Reinhardt, director of metallurgy and research, Youngstown (Pa.) Sheet and Tube Company, Youngstown, representing AISE.

Charles Schenck, research engineer, Bethlehem (Pa.) Steel Company, representing AISE.

A. G. Weigel, vice-president, Combustion Engineering Company, New York, N. Y.

Clyde Williams, National Defense Research Committee, Battelle Memorial Institute, Columbus, Ohio.

A. R. Wilson, engineer of bridges, Pennsylvania Railroad, Philadelphia.

R. E. Zimmerman, vice-president, United States Steel Corporation of Delaware, Pittsburgh, Pa.

W. Spraragen, *executive secretary*, Welding Research Council, New York, N. Y.

ANNUAL REPORT

The Engineering Foundation, established in 1914, completed its 30th fiscal year on September 30, 1944, and the chairman's report of the year's activities was presented to the AIEE and the other Founder Societies by A. L. Queneau at its annual meeting. The book value of the capital funds of the Foundation on September 30, 1944, was $962,000 compared with $959,000 on September 30, 1943. The income for the fiscal year 1943–44 was $35,472.76, as compared with $35,160.38 for the previous year 1942–43. For the fiscal year 1943–44 disbursements amounted to $22,750.78, as compared with $31,790.20 for year 1942–43. The balance on September 30, 1944, was $41,014.85 as compared with $28,292.87 on September 30, 1943.

As is customary the Foundation has contributed to a number of research projects in diverse fields of engineering and to the support of certain agencies having as their objective the advancement of the profession of engineering. Preference is given to projects of a fundamental nature, which normally would not be undertaken by industrial research organizations. In certain cases, where a group of industries are concerned, participation enables the Foundation to serve, as it were, as a catalysing agent for an undertaking, mainly supported by contributions from industry. In addition projects have been scrutinized with regard to their bearing on the war and have been encouraged only as they promised to contribute to the war effort. Because the Government through its various agencies is able to support any research project of probable importance to the war effort, the demand for support from an agency such as the Foundation is limited. Coupled with this is the fact that competent research personnel has been withdrawn largely from educational institutions to serve in Army, Navy, and other Government research and development activities. The result is a continuing lessened demand upon the Foundation's funds for the support of research projects and a reduction in the number of such projects. It is clear, however, that in the years following the war the need for engineering research in many fields will be recognized even more fully and in that period beyond any question the Foundation could employ profitably a much larger income than will be available from its present capital funds.

During the year 1943–44, work on seven projects has continued, for the year 1944–45 grants were recommended for continuation of work upon five projects and the initiation of three new projects.

A summary of the project with which AIEE has been directly concerned follows.

Welding Research Council. (Foundation grant $4,000. Chairman, Comfort A. Adams, E. G. Budd Manufacturing Company, Philadelphia, Pa.)

As a result of its eight years of operation the Welding Research Council has emerged as the recognized medium for co-operative welding research in this country, according to the report. Most of the interested engineering societies, trade associations, government departments, and industries interested in welding have come to look upon the Council as their welding-research organization. Many of the project committees of the Council have direct contacts in their particular fields through common membership with the technical committees of the American Welding Society, other engineering societies, and government departments. In this way their codes, specifications, and standards, and governmental reports immediately reflect the findings and knowledge gained through the research work of the Council. For example the "Handbook" and educational books of the American Welding Society have made full use of the reports of the Council.

Research has been continued actively under the various committees. In the opinion of the chairman the greatest single accomplishment of the Welding Research Council during the year was the arrival at a better understanding of the fundamentals of the two major problems which confront the welding industry, namely, weldability and weld stresses. Concise reports of the work of each of the project committees of the Council follow:

Aircraft Welding Committee (Chairman, G. S. Mikhalapov)—The Welding Research Council's committee in this field comprises the major scientific research talent engaged in aircraft-welding-research investigations. The American Welding Society has a somewhat similar body concerned with the standardization of the use of welding in aircraft construction. The work of the research committee forms a basis for the standardization activities. The interested government departments are co-operating and, in fact, supplying most of the necessary funds, although some of the member companies are contributing to the program.

Some nine reports have been published by the committee in the *Welding Research Supplement*, and there have been several confidential reports, not released for publication, issued by the National Advisory Committee for Aeronautics. These cover the investigations at Rensselaer Polytechnic Institute, Troy, N. Y., and at Battelle Memorial Institute, Columbus, Ohio.

Fatigue Testing (Structural) (Chairman, Jonathan Jones)—The principal subcommittees met in the spring of 1944 and the main committee in April 1944 to prepare extensions of the program at the University of Illinois, Urbana. Two bulletins, 344 and 350 of the Engineering Experiment Station, University of Illinois, appeared, giving the results of tests on butt, fillet, and plug welds. Three reports have been issued by the main committee. A fourth report on "The Fatigue Strength of Fillet, Plug, and Slot Welds," is receiving final review before publication. Pilot tests have been made to ascertain whether fatigue strength is reduced by the metallurgical heat effects of welding with mechanical stress raisers eliminated. The findings will be presented in the form of a paper at the forthcoming meeting of the Welding Society. These tests already are being followed by a more complete program aimed at exploring all important variables. A new large financial contributor, the American Iron and Steel Institute, has been added. In 1943, subcommittees on flexural members, and on bridge-reinforcement details were organized, both headed by representatives of the Association of American Railroads. The programs of these two subcommittees have formed a large part of the work in 1944.

High Alloys Committee (Chairman, S. L. Hoyt)—The committee has established two fellowships, one at Carnegie Institute of Technology, Pittsburgh, Pa., for work on stress corrosion of stainless steels and the other at Stevens Institute of Technology, Hoboken, N. J., for work on corrosion of stainless steels. The following reports were published during the year:

A first "Report on Stress Corrosion Cracking of Stainless Steel in Chloride Solutions," by M. A. Scheil, O. Zmeskal, J. Waber, and F. Stockhausen in October 1943; and a report, "Studies on Stress Corrosion Cracking of Austenitic Stainless Steels, Types 347 and 316," by M. A. Scheil and R. A. Huseby in August 1944.

Resistance Welding Committee—The resistance welding committee's activities have been divided between two subcommittees, one of them recently organized under the chairmanship of S. L. Hoyt, to study problems relating to flash welding of aluminum and its alloys, and the other on the general fundamentals of spot welding under the chairmanship of F. R. Hensel. The work of the last-named subcommittee has been continuing for several years at Rensselaer Polytechnic Institute under the supervision of Wendell F. Hess. During the past year the resistance welding activities of that laboratory have been concerned with the spot welding of heavy plate materials, including principally the more hardenable types used for military purposes. There also has been investigational work on the spot welding of SAE 1020 and *X*-4130 steels in the 0.125-inch gauge, and another investigation has involved the seam welding of monel metal.

Structural Steel Committee (Chairman, Lamotte Grover)—As in most university research, the investigations centered in the several universities have been retarded seriously by lack of research personnel. One report on "Tests of Welded Top-Plate and Seat Building Connection" by J. L. Brandes and R. M. Mains appeared in the March *Supplement*. Otherwise investigations at Le-

high University, Bethlehem, Pa., and at the Carnegie Institute of Technology have come to a standstill. Work continues on a limited scale at Columbia University, New York, N. Y., on the study of structural members under impact loads and the effect of impact on residual stresses in structural joints, particularly butt splices in heavy H-sections.

The committee initiated several new programs of investigations, one of which is the effect of residual stresses in different types of joints commonly used in ship construction and the related effect of propagation of cracking. The behavior of residual stresses in welded joints in thick material and under severely restrained conditions also will be studied, using specially constructed box-girder specimens. Both investigations will be carried out at the United States Bureau of Standards.

The United States Navy is co-operating by making available the results of experiments dealing with causes of brittle fractures under high stress concentrations, with and without strain aging under restrained conditions found in thick materials.

University Research Committee (Chairman, H. C. Boardman)—The university research committee also has been handicapped considerably because of lack of personnel to undertake welding research work under its direction. Although a great many welding investigations are being carried out at the universities, most of these have become affiliated either with government-sponsored projects or with the larger and immediate projects of the Welding Research Council.

Weldability Committee (Chairman, A. B. Kinzel)—Both Lehigh University and Rensselaer Polytechnic Institute, having worked out the metallurgical problem comprised in the heat-affected zone next to the weld and the factors involved therein, have concentrated on the problem of cracking in the weld proper, it being understood that the latter problem is associated intimately with the previous one. At Lehigh University a new type of specimen has been evolved, which will be described in detail as soon as government regulations permit. This specimen gives a quantitative index for the susceptibility to cracking of welds made in steels of various analyses and of the effect of welding-rod composition and welding procedure on this cracking tendency. It promises to be of very practical value in weld evaluation and specifications. At Rensselaer Polytechnic Institute the problem has been attacked from a more basic point of view with precise measurements of welding conditions and stresses which tend to or do produce cracks in the weld. This work already has shed considerable light on the important factors affecting this phenomenon. It is expected that as in the case of the studies of the zone next to the weld, the combined work of Lehigh University and Rensselaer Polytechnic Institute will give both, a better understanding of the phenomenon and a tool of direct application for the welding engineer.

Plans are under way for continuing at Battelle Memorial Institute weldability investigations with respect to carbon manganese steel. In addition to the work at Battelle Memorial Institute on bead hardness and bead-bend tests, financed by the committee, the following co-operators have furnished results on work on the same materials performed at their own expense: Naval Research Laboratories, covering a study of five types of weldability tests; Carnegie Illinois Steel Company, investigating tee-bend tests; and Climax Molybdenum Research Laboratories, making end-quench hardenability tests.

Weld Stress Committee (Chairman, E. Chapman)—Progress has been made in the study of the very complex problem of weld stresses. At the Massachusetts Institute of Technology, Cambridge, the committee has continued its investigations on the measurement and distribution of stresses across the thickness of a thick plate. Biaxial fatigue studies have been continued at Illinois Institute of Technology, Chicago.

The committee has formulated comprehensive programs on subjects and at institutions as indicated:

1. Residual stresses produced by various welding procedures, Massachusetts Institute of Technology.

2. Peening investigations, Polytechnic Institute of Brooklyn, N. Y.

3. Residual stresses under biaxial and triaxial condition and the use of high-speed rotating disk, Massachusetts Institute of Technology.

4. Strength and ductility of steel under conditions of multiaxial tension, Case School of Applied Science, Cleveland, Ohio.

5. Studies of the flow, fracture, and relaxation of steels under combined stresses at high temperature, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

6. Hemispherical shells subjected to static pressures, Pennsylvania State College.

7. Biaxial fatigue studies, Illinois Institute of Technology.

IEE Offers Reduced Subscription Rates

The Institution *Journal* and *Science Abstracts*, publications of the Institution of Electrical Engineers, London, England, are now available to AIEE members at a 50 per cent reduction in the regular subscription rate.

The *Institution Journal* consists of three parts: "General"; 12 issues beginning in January at two dollars per year, "Power Engineering"; six issues beginning in February at three dollars per year, and "Radio and Communication Engineering"; four quarterly issues beginning in March at two dollars per year. All three parts may be obtained for six dollars annually.

Science Abstracts, published in association with the British Physical Society, the American Physical Society, and the AIEE, is issued in two sections, "Physics Abstracts" and "Electrical Engineering Abstracts." The volume consists of 12 monthly issues starting in January. Each section is $3.50 per year or six dollars for both sections.

AIEE members desiring either or both publications should make payment through the AIEE.

Seattle Engineering Groups Form Puget Sound Council

Organization of the Puget Sound Council of Engineering and Technical Societies, a group of various engineering, architectural, and technical sections and chapters in Seattle, Wash., and vicinity, has been announced by C. H. Cutter (A '28), chairman of the AIEE Seattle Section.

The council is patterned after the national Engineers' Council for Professional Development and is the result of an idea brought back by Mr. Cutter from the AIEE summer technical meeting, St. Louis, Mo. Under this plan, local sections or chapters of national societies are banded together in a joint council. It is expected that membership will include approximately 20 societies. Representatives of AIEE on the Puget Sound Council are N. A. Carle (A '06, F '13) who is chairman and R. E. Kistler (A '17, M '30) who is secretary. R. L. Rockwell (A '13, M '22) vice-chairman, is representing the American Society of Mechanical Engineers. Treasurer of the council is LaMonte Shorett.

The Puget Sound Council's aim is to present the unified engineering profession's views on public matters to commissions or other public bodies. It expects to take an active part in the planning and construction of postwar projects, to concern itself with legislation having to do with code standardization, engineering licensing, and other nonpolitical matters, and to take an active interest in the re-establishment in civilian life of the engineers returning from military service.

LIBRARY

OPERATED jointly by the AIEE and the other Founder Societies, the Engineering Societies Library, 29 West 39th Street, New York 18, N. Y., offers a wide variety of services to members all over the world. Information about these services may be obtained on inquiry to the director.

Library Reports for 1943–44; New Officers Chosen

At the recent annual meeting of the Engineering Societies Library board, E. F. Church, Jr., was appointed chairman for 1944–45, and R. H. Barclay (F '28) was appointed vice-chairman. Harrison W. Craver was reappointed director of the library and secretary of the board.

Members of the library board are:

Terms expiring October 1945
Edward P. Hamilton, ASCE
W. A. Mudge, AIME
John Blizard, ASME
W. I. Slichter, AIEE

Terms expiring October 1946
Charles E. Trout, ASCE
Thomas T. Read, AIME

Terms expiring October 1947
J. K. Finch, ASCE
E. F. Church, Jr., ASME
George L. Knight, AIEE

Terms expiring October 1948
James W. Laist, AIME
P. H. Hardie, ASME
Nelson S. Hibshman, AIEE

Members-at-large
Sydney H. Ball
Robert H. Barclay
George F. Felker

Members of the executive committee for 1944–45 are:

E. P. Hamilton — George L. Knight
John Blizard — T. T. Read

ANNUAL REPORT

The annual report of the Engineering Societies Library for the year 1943–44 was submitted by Harrison W. Craver, director,

Operation of Library

Maintenance revenue	$48,945.44	
Maintenance expenditures	43,970.93	
Credit balance for year 1943–44	4,974.51	
Credit balance from previous years	18,134.16	
Credit balance September 30, 1944		$23,108.67
Service bureau revenue	$25,852.76	
Service bureau expenditures	18,909.23	
Credit balance for year 1943–44	6,943.53	
Credit balance from previous years	8,227.48	
Credit balance September 30, 1944		15,171.01
Total net operating credit balance cumulated to September 30, 1944		$38,279.68

Library Services

	1941–42	1942–43	1943–44
Visitors	23,734	22,260	21,992
Other users	10,648	13,579	15,147
Total	34,382	35,839	37,139
Photostat orders	3,046	3,487	4,029
Photostat prints made	31,254	38,702	53,518
Telephone inquiries	6,097	6,689	6,700
Borrowers	650	1,055	1,133
Books lent	846	1,393	1,533
Searches and copies	103	86	114
Translations	35	30	53
Total acquisitions	10,163	10,286	8,104
Books reviewed	498	420	364
Library inventory			
Volumes in library	154,873	156,780	158,521
Maps	7,859	7,872	8,392
Searches	4,525	4,565	4,654
Total	167,257	169,216	171,567

to the AIEE and the other Founder Societies in tabular form. The accompanying tables show an increase in the total number of users and a greater proportion of nonvisitors using the library. The demand for photostats also has been a record one. Additions to the book collection have declined because of wartime curtailment of supplies from Europe. Expenditures were kept well within the budgeted amounts.

OTHER SOCIETIES •

CEMA Opens Headquarters In Toronto, Canada

A Canadian Electrical Manufacturers Association which will perform for the Canadian industry a function similar to that filled by the National Electrical Manufacturers Association in the United States has established its headquarters in Toronto. The new organization generalized its objects as the promotion and furthering of the interests of manufacturers of electrical products and the interests of the public in manufacturing, engineering, safety, transportation, and other matters.

Specific aims listed by the association are:

1. To increase the amount and improve the quality of electrical service to the public.

2. To promote the standardization of electrical products.

3. To collect information relating to the industry and to disseminate such information to members of the Association and to the public.

4. To appear for the members of the CEMA before and to co-operate with legislative committees, government departments, and other bodies on matters affecting the industry.

5. To attain improved production, enlarged distribution, and increased efficiency in the use of electrical products.

The Association already has inaugurated its program of activities by setting up a War Assets Corporation to assist in the disposal of war equipment surpluses and is developing a Farm Electrification Council to sponsor the expansion of electrical services in rural areas. The Association hopes to realize this latter project by encouraging simplification of design and improved distribution with their consequent reduction in cost.

An effort will be made to avoid having the services offered by CEMA overlap those of the Canadian Manufacturers Association and the Canadian Standards Association.

R. D. Kerby of Toronto, formerly executive assistant to the president of Research Enterprises Ltd., and a founder and first president of the Canadian Automobile Chamber of Commerce, has been appointed general manager of CEMA.

ASME Council Approves Proposed Organization Changes

The recent report of the special committee on society organization structure of the American Society of Mechanical Engineers, which considered recommendations concerning geographic divisions and representation, committee responsibility, efficiency of organization, and the responsibilities of the secretary of the society, was approved by the ASME council at its meeting of December 1, 1944. This report proposed several changes in the structure of the society.

Geographically, there will be a division of the United States into eight districts, each headed by a vice-president nominated by, and responsible for, that district. This system is patterned after that in successful operation in the AIEE and is intended to provide a more direct representation than does the present ASME scheme. Although no change will be made in the method of electing managers, the title of director has been substituted for that of manager as one which is used more uniformly to designate such offices, and the elections of both vice-presidents and directors will be staggered as to time. To effect this, four vice-presidents will be elected each year and two directors at large each year.

In the matter of committee responsibility, in order to allow both the council and the executive committee more freedom for the consideration of general policy and the formulation of long-term plans for the benefit of the society, boards of control will be set up with jurisdiction over committees in their respective fields. All existing operating committees will report to one of the boards recommended, and the board, in turn, will submit reports to the Council, as only matters of policy need the council's attention and action.

No change is contemplated in important agencies of the society such as the boiler code and test code committees, as it is important that neither their responsibilities nor their prestige be curtailed. The function of the boards of control is to be that of responsible co-ordinating and screening agents to which is delegated authority from the council to pass on matters handed up to them and to make recommendations for council approval of codes and standards and for committee appointments.

In addition, to contribute to the efficiency of the headquarters organization, it has been recommended that several competent assistants be added who are preferably younger than 40 years and in no case older. Although some difficulty is expected in finding suitable men at this time, the end of the war should make available much excellent material.

AAAS Elects Officers for 1945

Charles F. Kettering (F '14) vice-president of General Motors Corporation, Dayton, Ohio, was elected president of the American Association for the Advancement of Science at the annual meeting of the association held in December. At that time vice-presidents for the various branches of science were elected. Those elected are:

Mathematics—E. P. Lane, University of Chicago, Ill.

Physics—R. C. Gibbs, Cornell University, Ithaca, N. Y.

Chemistry—Henry Eyring, Princeton, N. J.

Astronomy—J. J. Nassau, Case School of Applied Science, Cleveland, Ohio.

Geology and Geography—Arthur Beven, University of Virginia, Charlotteville.

Zoology—Carl G. Hartman, University of Illinois, Urbana.

Botany—F. D. Kern, Pennsylvania State College, State College.

Anthropology—A. Irving Hallowell, Northwestern University, Evanston, Ill.

Psychology—Florence Goodenough, University of Minnesota, Minneapolis.

History and Philosophy of Science—John F. Fulton, Yale University, New Haven, Conn.

Engineering—George A. Stetson, *Mechanical Engineering*, New York, N. Y.

Medical Sciences—Warfield T. Longcope, Johns Hopkins University, Baltimore, Md.

Agriculture—William Albrecht, University of Missouri, Columbia.

Education—H. H. Remmers, Purdue University, Lafayette, Ind.

Otis Caldwell of the Boyce Thompson Institute is general secretary of the association, F. R. Moulton is permanent secretary, and W. E. Wrather of the United States Geographical Survey is treasurer.

RMA Cancels Winter Conference and Probably Trade Show

In compliance with the recent request of James F. Byrnes, director of the Office of War Mobilization for voluntary reduction in travel and attendance at industry meeting, trade shows, and conferences, cancellation of the midwinter conference of the Radio Manufacturers Association has been announced by R. C. Cosgrove, president of RMA.

All committee and group meetings planned for the conference originally scheduled for February 19 to 21 in New York, N. Y., have been abandoned, but a meeting of the board

of directors will be held on February 21, as it involves less than 50 persons, the limit recommended for such meetings by the committee executing Director Byrnes' order. Other division and committee meetings involved in the blanket cancellation of the mid-winter conference may be held separately later with minimum travel and hotel requirements.

An RMA trade parts show planned by the RMA contingent upon the defeat of Germany by April 1 probably will be canceled at the association's next board of directors meeting, since the OWM request singles out postwar trade shows for disapproval.

Plans for the annual RMA war-production conference and annual membership meeting scheduled for next June in Chicago, Ill., are going forward on a much reduced scale. It is expected that attendance will be limited to official delegates and groups directly connected with the war program.

AIME Cancels General Meeting

In conformation with the recently published request of James F. Byrnes, Director, War Mobilization and Reconversion, to conserve transportation the American Institute of Mining and Metallurgical Engineers has announced the cancellation of its 162d general meeting, scheduled for New York, N. Y., February 19–22, 1945.

The technical papers which were to have been presented at the meeting will be made available to members through the various AIME publications.

ASRE Periodical Will Appear in Fall of 1945

The first issue of *Refrigeration Abstracts*, a new publication venture for the American Society of Refrigerating Engineers, is scheduled for sometime in the fall of 1945. The magazine, which will be issued biannually for the duration of the war, will condense current refrigeration publications of engineering and scientific value, encompassing both English- and foreign-language material. After the war, when paper supply will not be a determining factor, it is planned to increase the yearly issues to six.

J. Mack Tucker, associate professor of mechanical engineering at the University of Tennessee and a contributor to *Refrigerating Engineering* and the "Refrigerating Data Book," has been chosen editor of the *Abstracts*.

IRE Initiates Building-Fund Campaign. A campaign to raise a $500,000 building fund in anticipation of postwar expansion of its service to the electronic and communication industries, was inaugurated by the Institute of Radio Engineers during its winter technical meeting held in New York, N. Y., in January. Actual building plans will remain flexible to permit establishing the new quarters jointly with other engineering and scientific societies, if this should prove desirable, the directors of the society announced.

LETTERS TO THE EDITOR

INSTITUTE members and subscribers are invited to contribute to these columns expressions of opinion dealing with published articles, technical papers, or other subjects of general professional interest. While endeavoring to publish as many letters as possible, Electrical Engineering reserves the right to publish them in whole or in part or to reject them entirely. Statements in letters are expressly understood to be made by the writers. Publication here in no wise constitutes endorsement or recognition by the AIEE. All letters submitted for publication should be typewritten, double-spaced, not carbon copies. Any illustrations should be submitted in duplicate, one copy an inked drawing without lettering, the other lettered. Captions should be supplied for all illustrations.

Influence of Research on Engineering Developments

To the Editor:

The third paragraph of L. W. Chubb's article, "Influence of Research on Engineering Developments" (*EE, Dec. '44, p 443–4*) contains astonishing statements regarding the World War I status of airplanes and automotive transport.

In 1918 hundreds of airplanes were functioning, and thousands of American trucks were delivering supplies to the front in France. Of course, railroads handled the bulk of the freight in the rear areas because of their greater efficiency.

Since 1918 outstanding improvements have been made in these types of transportation, particularly in airplanes, as a result of experience as well as scientific research. However, if available, railroads still handle the bulk of the freight for the same reason as before.

C. T. WELLER (M '21)

(Electrical engineer, General Electric Company, Schenectady, N. Y.)

Postwar Curriculums in Electrical Engineering

To the Editor:

I think the article, "Postwar Curriculums in Electrical Engineering," by R. G. Kloeffler (*EE, Oct. '44, p. 364–7*) and the letter to the editor from H. L. Abbott (*EE, Dec. '44, p. 458–9*) are very constructive.

I hesitate a little to give you my own opinion, as I did not have the fortune of being brought up in this country. However, in some respects it may be of interest to compare the European practice with the one in use here.

One condition for graduation which I think is very important is the required proof of one full year's work in factories in basic operations. It is so arranged abroad that there is a lapse of six months between graduation from high school and the start of the first semester of college in order to allow a half year's work before going to college; the balance of the work usually is arranged during the summer vacations. To illustrate the point I give you my own schedule:

First 26 weeks:	
Four weeks each—	Foundry
	Pattern shop
	Machine shop: lathe
Two weeks each—	Machine shop: milling machine
	Tool room: hardening and precision grinding
	Forge shop
	Sheet-metal work
Six weeks—	General assembly including welding
Next three months:	All different operations in an electric instrument plant
Next two months:	A-c and d-c winding, motor, and transformer assembly
Final two months:	General work in electric shop of power plant

Besides this factory practice, the electrical-engineering curriculum contains considerably more mechanical-engineering subjects, as the two departments are two subdivisions of one major department abroad. A basic course in civil engineering is compulsory, and accounting is taught with considerable detail.

The fact that a much smaller percentage of students goes to high school in Europe allows a certain selectivity which results in teaching a major portion of basic subjects in high school, freeing the freshman year of college for more advanced subjects. At the same time the higher level of the high schools takes care of the literary, humanitarian, and biological subjects advocated in the previous articles.

JACK M. NOY (A '43)

(Electrical engineer, Climax Molybdenum Company of Pennsylvania, Langeloth)

NEW BOOKS • • •

The following new books are among those recently received from the publishers. Books designated ESL are available at the Engineering Societies Library; these and thousands of other technical books may be borrowed from the library by mail by AIEE members. The Institute assumes no responsibility for statements made in the following summaries, information for which is taken from the prefaces of the books. All inquiries relating to the purchase of any book reviewed in these columns should be addressed to the publisher of the book in question.

Battery-Electric Vehicles. By S. M. Hills. George Newnes, Ltd., Tower House, Southampton Street, Strand, London, W.C.2, England, 1943. 206 pages, illustrated, 9 by 6¼ inches, cloth, 12*s*.6*d*. (ESL.)

This book deals with all types of battery-operated electric vehicles and their accessories, including light and heavy trucks, tractors, locomotives, busses, passenger cars, and so forth. Batteries, charging equipment, and care and maintenance are discussed as well. The possible fields of use are pointed out, and British practice is thoroughly reviewed. There is a bibliography which is confined to British publications. This is the first book on the subject in 25 years.

Henley's Twentieth Century Book of Formulas, Processes and Trade Secrets. Edited by G. D. Hiscox, 1944; revised and enlarged edition by T. O. Sloane. Norman W. Henley Publishing Company, New York, N. Y., 1944. 865 pages, illustrated, 8½ by 5½ inches, cloth, $4. (ESL.)

This well-known collection of recipes, formulas, and processes has been revised again. New formulas have been added and new sections included on plastics and on photography. Old formulas have been replaced by better ones.

TRANSACTIONS SECTION

Preprint of Corresponding Pages From the Current Annual AIEE Transactions Volume

Electrification and Signaling of the Canadian National Railways Terminal, Montreal, Canada

R. G. GAGE
NONMEMBER AIEE

THE development of the Montreal Terminal of the Canadian National Railways, which was started in 1931 and lay dormant all during the depression years, was revived as an unemployment relief measure and continued as a wartime measure in 1939. The project consisted of centralizing the four passenger stations, the construction of a new station, and the alteration of existing freight yards and facilities.

The Canadian National Railways' facilities at Montreal are a combination of those of the Grand Trunk Railway and Canadian Northern Railway, both of which, together with the Canadian Government Railways, were combined to form the Canadian National Railways System in Canada. The use of Bonaventure station, the old and outmoded terminal of the Grand Trunk Railway and Canadian Government Railways, for many years had been the cause of congestion and, owing to the numerous grade crossings of city streets involved, had been a source of serious city complaints.

During its construction, the only way the Canadian Northern Railway could enter Montreal for its eastern terminus was by way of a three-mile double-track tunnel under Mount Royal, terminating in a passenger station at Lagauchetiere Street, adjacent to the uptown retail business district of the city. Having to operate through this long tunnel, the Canadian Northern Railway was forced to electrify its lines for a distance of about ten miles, including the tunnel, and one of the then (1914) modern and popular systems, namely 2,400-volt d-c, was adopted. Six 1,000-horsepower locomotive units were built by the General Electric and the Canadian General Electric companies and eight multiple-unit car equipments were provided, two of which were subsequently installed.

After an exhaustive study just prior to 1930, it was decided to develop the new terminal on an enlargement of the original Canadian Northern station site. This now comprises 14 passenger- and three express-station tracks, of which the four through tracks in the center have platforms long enough to accommodate 20-car trains. These station tracks connect with the double track of the Mount Royal Tunnel on the north and with six main tracks, tapering down to two, on a viaduct extending southward to the Victoria Bridge. The station building is centrally located in relation to the platforms, reducing to the minimum the distance which passengers must cover in boarding or leaving trains. The platforms are of car floor height and are served by two broad stairways and an escalator leading directly on to the center line through the station concourse, immediately above. The subtrack area, extending throughout the station area, provides the express, baggage, mail, and customs facilities and is accessible by motor or truck directly from Lagauchetiere Street, one of the main thoroughfares. Access to the station proper by taxi and private automobile is from two plazas located on the north and south sides, connecting directly to the adjacent streets. Direct access for pedestrians is by means of stairs and escalators at both the east and west sides from Dorchester Street. The two upper floors of the station building are occupied by the railway operating staff.

As will be gathered, the entire station area is below the adjoining street levels, primarily on account of the elevation of the tracks in the Mount Royal Tunnel which is also the elevation of the track on Victoria Bridge leading across the St. Lawrence River. The tracks between these two points are constructed on a viaduct, thereby securing grade separation of all intervening city streets. The entire project has been laid out in such a way that the overhead rights for office buildings, hotel, auditorium, and so forth may be built without interfering with any of the existing structures as provision has been made for the necessary supporting foundations for such buildings. It is felt well within the realm of possibility that, with the normal growth of Montreal, this terminal area will develop in a similar manner to that of Grand Central Terminal in New York.

Electrification

Power for the Montreal Terminal is purchased from the Quebec Hydro Commission at three phase, 12,000 volts, being received from two independent substations which, together with six other substations, are connected to the 66,000-volt ring of the power distribution system. The two supply lines terminate in a railway transformer substation, located below the tracks in the station area, each line having capacity to carry the total terminal load of approximately 6,000 kva. The main circuit breakers on each of these supply cables are equipped with an automatic change-over device ensuring the continuity of service in case of trouble arising in the cable itself or in the substation feeding it. This 12,000-volt supply is stepped down to 4,000 volts, three phase for general distributions; 208/120 volts, three phase, four wire for general lighting and car charging purposes; and 575 volts, three phase for station elevators, fan motors, pumps, and so forth. Two independent three-phase 4,000-volt circuits are run in conduit from this substation to the central control tower at the Lachine

Paper 43-10, recommended by the AIEE committee on land transportation for presentation at the AIEE winter technical meeting, New York, N. Y., January 29-26, 1945. Manuscript submitted October 25, 1944; made available for printing November 20, 1944.

R. G. GAGE is chief electrical engineer, Canadian National Railways, Montreal, Quebec, Canada.

Electric locomotives and trolley feeder breakers were manufactured by the English Electric Company, London, England, and purchased from the Montreal Harbour Commission. Glass-bulb rectifiers and rectifier transformers were supplied by the Hewittic Electric Company Ltd., Hersham (Walton-on-Thames) Surrey, England, through the Northern Electric Company at Montreal. Overhead trolley fittings were supplied by the Ohio Brass Company, Mansfield, whose engineers were also consulted in the design and application.

Signal equipment for the Montreal area was purchased from the Union Switch and Signal Company, Pittsburgh, Pa., who are also responsible for the detail engineering and construction. Signal equipment for the St. Lambert area was purchased from the General Railway Signal Company, Rochester, N. Y., who are also responsible for the detail engineering and construction.

All of the above work was carried out by the chief engineer of the Canadian National Railways, under the immediate supervision of the chief electrical engineer and his staff.

Canal lift bridge to supply energy for the operation of the lift bridge over the canal and for the terminal signaling.

The feature of the power system for the terminal which is of special interest is the use of glass-bulb mercury-arc rectifiers for supplying the 2,400-volt direct current for traction. Although these are used to a considerable extent for traction purposes in England and in other parts of the Commonwealth, it is their first use in Canada and probably any place in 2,400-volt service.

Two independent 12,000-volt three-phase circuits are run from the transformer station and, protected by main circuit breakers connected with two 2,156-kva 12,000/2,200-volt 3- to 12-phase rectifier transformers. Each transformer feeds a bank of four glass-bulb rectifiers whose capacity under normal rating is 1,500 kw per bank and 3,000 kw on a five-minute peak rating. The 12 phases in each transformer are connected in two three-phase groups joined at their neutral points by an interphase transformer; these two six-phase groups are in turn connected together at their neutral points by a third interphase transformer. The rectifiers are operated in pairs connected in parallel across six phases. Bulbs *A* and *B* are connected to the six phases comprising group one and bulbs *C* and *D* to the six phases comprising group two. Each bank is protected by a 2,400-volt d-c breaker with a normal time lag set to take care of the normal operating short-period peak loads but with a very high-speed setting for reverse current, protecting against reverse flow between banks in case of a backfire in the bulb.

The chief reasons for the selection of glass-bulb rectifiers instead of the more familiar steel-tank type were the decidedly lower cost to install; a much better delivery date under wartime conditions; the advantage of having the installed capacity in eight equal units instead of two; the elimination of all vacuum and cooling auxiliaries; and the excellent reported record in service on British railways.

The rectifiers consist of vacuum-sealed glass bulbs fitted with six operating anodes, each protected with a fuse, two exciting anodes, and an auxiliary automatic-starting anode. A pool of mercury covers the cathode located in the base of the bulb. The bulbs are mounted in steel cabinets with open grille doors for purposes of ventilation and are cooled by a fan located immediately beneath the bulb and connected so that its speed increases with the total current in the rectifier. The life of the tubes, as indicated by the records in other railway installations, is a matter of years. Individual failures, of course, occur as a result of defective workmanship or material as in all types of equipment.

The rectifier is started by energizing the 120-volt auxiliary circuit, which operates a magnetic contactor whose function is to cause a flexible contact to dip into the mercury pool and, when withdrawn, to strike an arc. This arc energizes the exciting circuit and maintains continuous arcing on the exciter electrodes which in turn is automatically transferred to the load anodes upon the application of load. Inasmuch as the rectifier has a permanent vacuum, no preliminary time is required for auxiliaries and the rectifier can take on its load immediately upon demand. It can, therefore, be thrown on or off the line from remote control points, or could be controlled by a time switch if desired. By the use of a large number of anodes in multiple, 24 in this case, and the reduction of current concentration on the anodes, backfiring is eliminated, or at least none has taken place to date.

The transformers are of the oil-insulated self-cooled type, 3-to-12 phase, housing the interphase transformers, the auxiliary starting transformer, and a choke in the main rectifier circuit which controls the cooling-fan speed in proportion to the load.

The rectifier station is designed for remote control and to be operated without continuous attendance. The rectifier banks can be put on or off the line independently from manually operated remote-control points from the substation or at the interlocking control tower at the Lachine Canal.

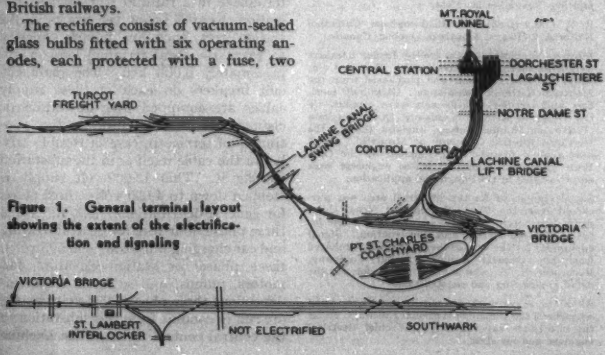

Figure 1. General terminal layout showing the extent of the electrification and signaling

Figure 2. Rectifier station showing the two banks of rectifiers, one on each side of the center aisle, with three of the trolley section breakers in the far end

In order to overcome interference with telegraph and telephone communications, corrective equipment was installed consisting of a coil of 30 turns and 1.115 millihenries inductance in the negative return and four tuned shunts between the positive and negative to eliminate the 360, 720, 1,080, and 1,440 frequencies. The rectifiers are operated without interference with existing communication circuits.

In addition to the mercury-arc rectifier station, direct current is supplied from a motor generator substation originally installed by the Canadian Northern Railway in 1918. This station consists of two three-unit sets composed of a 12,000-volt synchronous motor and two 1,200-volt 1,500 kw d-c generators connected in series. This station is being held as a reserve and will, undoubtedly, be replaced by modern rectifiers when the electrification is extended.

The catenary system throughout the terminal consists of steel bridges spanning the main line tracks spaced on an average of 180 feet apart, carrying copper conductors of approximately 800,000 circular mils equivalent copper conductivity per track, made up of a Copperweld and copper main messenger, copper auxiliary messenger, and two bronze grooved trolley wires. The trolley system is divided into 12 sections, each provided with a feeder breaker. Seven of these breakers, with an auxiliary for emergency use, are installed in the rectifier substation, and the balance in the switching room of the interlocking tower at the canal. All the breakers are remotely controlled by push-button switches mounted on the signal control panel in the operating tower. The signal levermen, under the direction of the train controller, are thus able to

Figure 3. Interior of rectifier cubicle

energize or de-energize any trolley section as called for by the exigencies of the service. They also control the rectifier station, putting either or both banks on or off the line as required.

There are no special engineering features in the overhead system. It conforms to recognized good practice for heavy-duty electrification. Owing to the steel shortage under war conditions, the catenary bridges are lacking in uniformity. At first they were designed and fabricated from new material, then from second-hand bridge steel removed from railway bridges and, finally, from creosoted timber when steel became unprocurable.

The additional electric locomotives necessary for an enlarged electrical operation, together with the feeder breakers for the 12 trolley sections, were obtained from the Montreal Harbour Commission as a result of their termination of electrical operation. The electrical characteristics of the Harbour installation were by design the same as those of the original Canadian Northern installation, so that it would be possible for the Canadian Northern to operate on the Harbour trackage in the interchange service.

Throughout the electrified zone, one rail of each track is bonded for propulsion return currents and the several return rails in parallel tracks are cross bonded together for conductivity. Owing to the use of direct current for propulsion, it was necessary to install a-c signal track circuits. Complications in the layout in some of the tracks, as well their cost, made it desirable to avoid the use of impedance bonds as frequently used with signal systems on electrified lines. This bonded return rail is used as a common rail for both signaling and traction, the other rail being insulated and retained for signaling.

A new coachyard was built at Point St. Charles consisting of 32 tracks, 19 of which were electrified, lighted, and equipped with battery-charging, vacuum, and steam-heating facilities. The overhead consists of the lightest type of street-railway construction with the trolley carried from single cross messengers spaced at 80-foot centers. Thirty-three-foot 85-pound scrap rails, with the ends embedded about five feet in concrete, are used as the trolley supports. The stresses in the trolley wires, as well as in the cross spans, are taken care of by dead-end guying. On each alternate support in the longitudinal rows, and staggered as between rows, is mounted a 6,000-lumen 20-ampere series lamp for lighting the yard. The lamps are supported in a hoop-type bracket mounted on the top of the trolley supporting poles giving a height above rail of about 28 feet. The lamps are fitted with symmetric refractors and are arranged in four regulated circuits. Very satisfactory and uniform lighting throughout the yard area has been obtained.

A rather novel feature in this yard is the arrangement of the car-charging facilities. The constant-potential system is used, supplemented by portable chargers to take care of the occasional car requiring special attention, such as those fitted with Edison batteries requiring a higher charging voltage.

Owing to the large variations in the total car-charging load, the usual practice of having two car-charging generator sets, with which at least one relatively large set would be running with a very light load for a considerable portion of the day, it was decided to install 16 500-ampere 50-volt motor generator sets located on the midway through the center of the platforms and at the approximate center of the loads. Owing to the relatively narrow platforms, these sets were mounted in small houses about 15 feet above the platforms, thus permitting the ordinary use of platform trucks necessary in the servicing of trains.

The houses, which also accommodate the regulating equipment, are accessible through a trap door in the floor. Windows provide ventilation in the summer and heat generated by the sets themselves provides the necessary heat in winter. The wiring for each platform is the three-wire return-loop system with the operating coils of the voltage regulator connected across, thus maintaining a constant potential at all charging outlets. Each generator is protected by a current regulator, a fuse, and a reverse-current relay. There is also a magnetic starter with start–stop push-button control at the base of each house support. A series relay is connected to the d-c side which serves to automatically stop the set when the last car is taken off charge. This relay also makes it necessary to have at least one car on the circuit before the motor generator set will run.

Signaling

The signaled area is divided into two parts, that on the south or east side of the St. Lawrence River—comprising two main tracks with connections to a large freight yard at Southwark—extends from St. Lambert for four route miles eastward and represents 108 controlled functions; the balance on the north or west side of the river extends from the west end of Turcot freight yard through the station area into the Mount Royal Tunnel and includes main tracks varying from two to six and their connections to the 17 station tracks. This latter installation covers about eight route miles and comprises 607 controlled functions. The former, which is controlled from the tower at St. Lambert, is what is known as wire-controlled relay interlocking and is divided into four zones. Inasmuch as this territory is not electrified, but is in close proximity to electrified lines, two-rail a-c track circuits are used. The Montreal side consists of relay interlocking laid out in ten zones, each of which is connected with the operating tower at the Lachine Canal lift bridge by means of polar code control. As all of this area is electrified, single-rail a-c track circuits are used throughout.

All main-line tracks throughout the aforementioned entire areas are provided with signals for movements in both directions and trains are governed by signal

Figure 4. Control panel of the St. Lambert interlocker showing signal buttons in the tracks and switch levers below

Figure 5. Operating panel and track diagram of Montreal interlocker showing the switch and signal push-turn buttons on the panel. Those in the triangular portions control the arc rectifiers and the trolley-feeder-section breakers

indication only. All relay racks and panels were wired in the factory before shipment and all relays are of the plug-in type which permits replacement without interfering with the permanent wiring and with minimum interruption to the service.

All signals are of the searchlight type using ten-watt ten-volt precision-based lamps, giving a strong parallel light beam which is clearly seen in bright daylight. This signal consists of a relay mechanism carrying three small colored screens on its armature, so arranged to show green with one polarity on the relay, yellow on the opposite polarity, and red when the relay is de-energized. The signal also includes a well-designed lens system producing a well-defined light beam. The signals at St. Lambert are of the standard interlocking type mounted on high ground masts or bridges for main-track movements and single-light dwarf signals for inferior-track movements, whereas all signals on the Montreal side are of the two-unit, low, ground type. The color aspects as shown by the signals are the usual: *green*—"proceed"; *yellow*—"proceed, expecting to find the next signal at stop"; and *red*—"stop." On the Montreal side, and at some points on the St. Lambert side, an aspect of red over yellow is displayed with the meaning to "proceed expecting to find the immediate block occupied." This means that an engineer accepting a red over yellow signal moves upon his own responsibility. This signal is necessary in terminal operation to enable locomotives to enter a block to connect with a train either in switching or in engine-changing operation. Dwarf, that is, low ground-type, signals are used in the Montreal interlocker throughout in order to utilize the trackage to the fullest extent and also to enable the signal to be located at the point at which it governs. The use of the low signals at Montreal also very greatly simplifies construction by separating the signals from interference with the electrified overhead system.

The interlocking machine at St. Lambert is made of a black-on-white laminated-plastic panel with the tracks milled out, showing a permanently white track diagram on a black background. All the switches are equipped with point indicators, which correspond to the operation of switch points in the track and offer a continuous broad white line, indicating the route which has been set up for a train movement. Signals are shown by illuminated push buttons located in the track where the signal is located. A green light in this button indicates that the signal is in the "proceed" position. The switches are controlled by small key switches located on the panel directly below the function. Miniature lamps located in each track section show by a red light the position of all trains throughout the interlocked area.

The Montreal interlocking machine, owing to the number of functions controlled by it, consists of an operating panel and a track diagram. The operating panel is of the desk type with an inclined top, similar to the control panel in many a-c power stations. The switches and signals are controlled by miniature push-and-turn type switches on the panel, located in convenient groups in relation to the functions controlled and as shown on the track diagram. The track diagram is a large elevated vertical panel on which is painted in colors the various track circuits throughout the controlled area. Each track section is fitted with a lamp which shows by a red light when the track is occupied. Signal locations are indicated by lamps adjacent to the track governed which, when lighted with a green light, show that the signal is in the "proceed" position. All signal lights are put out when passed by a train and the red track-occupancy lamp goes out as soon as a train passes the immediate track section. It will thus be seen that the progress of a train throughout the interlocked territory can easily be followed by the train controller. This is very different from former times. Now, regardless of the distance a train is from the tower, or of the weather conditions prevailing along the track, the controller is continuously informed as to the position of all trains in his territory.

In two respects the Montreal installation is of particular interest to the engineering profession. The first is the area over which the control of the track switches and signals is centralized in this one machine. This perhaps is unique at the present moment, as the ten controlled zones comprising the interlocker would formerly have been controlled by perhaps five or six independent interlockers. The second point, and one which made this centralization of control possible, is the use of a high-speed code connecting the control machine with a bungalow or control point in each of the ten zones. The coding is performed over a set of six wires, three of which are reserved for the outgoing control code and three for the incoming indication code. The code itself consists of a series of d-c pulses, in which two line wires are alternately energized and de-energized. During the energized periods the line circuit may be of either positive or negative polarity. Only two wires are used during coding, the three wires being used to determine the polarity of the line circuit.

When the signalman depresses a switch or signal-control button on the control panel, he initiates a control code, which, after passing through the proper interlocking relay group, passes over the control-code line circuit to a control-reception panel in the zone bungalow, then to the function-control relays and finally to the wayside relays and apparatus, that is, to the switch-point operating mechanism or signal. When the function has operated in accordance with the code sent out from the control tower, the completion of such operation initiates a corresponding indication code which runs through corresponding relay groups and over the indication-line circuit, back to the control machine in the case of a switch-point operation, and to the track diagram in the case of a signal operation, thus, by means of indication lamps, informing the signalman that his instruction has been completed. This code is unique in the speed with which it operates, namely 35 pulses per second.

The fact that the entire Montreal Terminal area has been equipped with signals so that trains may run in either direction on all the main tracks and that train operation is entirely by signal indication, without the use of train orders, has resulted in a very great reduction in freight-train delays. The operation of the terminal since the opening of the Central Station in July 1943 would indicate that the centralizing of signal control over a relatively large terminal area is feasible and economical, and that the combination of the duties of signalmen in controlling the movements of trains, as well as controlling by remote operation the trolley-feeder switches of the electrified zones, is also practicable, and that the men readily learn and appreciate the functions of the equipment which they are asked to control.

A Modulated-Frequency System of Telemetering

HAROLD E. RENFRO
NONMEMBER AIEE

ARTHUR PERRY PETERSON
ASSOCIATE AIEE

WITH today's centralized control and supervision of power systems, it is essential that the man at the controls knows what is going on at all outlying stations and interconnection points. Telemetering equipment keeps him informed of load changes, transfer of power from one system to another, variations in voltage, and all other values that are necessary for efficient operation.

No one system of telemetering can meet all requirements. The speed of indication, accuracy, number of separate channels available, dependability, ease of totalizing, freedom from interference, the availability and need of repair parts, and the initial cost, as well as maintenance cost, are factors that determine the design of any system of remote metering. A résumé of the telemetering practice up to 1941 will be found in the report of the joint committee of the AIEE committee on automatic stations and the AIEE committee on instruments and measurements, published in October 1941. That report also contains an excellent bibliography on telemetering systems and methods.

When the Department of Lighting of the City of Seattle wanted a telemetering system which would operate over a carrier-current channel they were unable to locate such a system that would give them continuous and instantaneous readings. They felt that, for their purposes, an impulse system which provided readings at regular intervals was not the answer to their problem. Furthermore, they wanted a system that would permit several readings simultaneously over a single set of conductors. It was this need that led to the development of a modulated-frequency system of carrier telemetering.

The telemetering system herein described was designed to give continuous and almost instantaneous readings which are independent of supply voltage and are not affected by wide variations in remote-line characteristics. It was designed to operate with a high degree of dependability during emergencies, to permit a large number of channels on one pair of conductors, to give very fast response, and to incorporate certain other desirable features.

The transmitter generates its own carrier frequency making it unnecessary to provide a separate carrier-current system. Standard radio receiver tubes are used throughout and all parts subject to wear or breakdown are easily replaceable standard radio parts.

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HAROLD E. RENFRO is an engineer in the Department of Lighting of the City of Seattle, Wash., and ARTHUR PERRY PETERSON is president of the Control Corporation, Minneapolis, Minn.

General

The block diagram, Figure 4, illustrates the principle of operation and this will be described briefly. In the telemeter transmitter is incorporated the primary instrument, such as a wattmeter, which determines the values to be transmitted. This primary instrument controls the frequencies of two high-frequency oscillators whose outputs are converted into a single beat frequency. The beat frequency, which varies with the magnitude of the quantity being measured, is amplified and transmitted over the line, whether it be a transmission line or a telephone line. Normally, capacitive coupling is used with a transmission line whereas inductive coupling, with a band-pass filter to separate the carrier frequencies from the voice frequencies, is used with a telephone line. Only telephone-line applications will be described here.

At the receiving point the incoming signal from the line is amplified and then mixed with the output of a local oscillator of constant frequency. This converter stage is followed by a low-pass filter which attenuates all but the beat frequency. The current at this beat frequency is then amplified and fed into a frequency meter, of which the final indicating instrument is a part.

Transmitter

The schematic diagram of the telemeter transmitter is shown in Figure 6. The primary instrument actuates two variable capacitors, C_1 and C_2, which, in turn, simultaneously control the frequencies of the two oscillators. The variable capacitors form part of the capacitance of the frequency-determining resonant circuit of each oscillator.

The greatest difficulty with instruments of this type that have been tried in the past has been that a variable capacitor on the shaft of the primary instrument develops a torque of its own that varies with the potential applied to it. A variable inductance develops a somewhat similar torque due to current through it. This destroys the calibration of the instrument and makes a reliable system impossible, unless counter measures are taken.

An analysis of the torque developed by a variable capacitor with a voltage across its plates shows the following to be true: two conductors separated by an insulator tend to move toward each other when a difference of potential exists between them. With parallel-plane conductors of infinite area, this force is perpendicular

Figure 1. Front view of the assembled telemeter transmitter

The two wrought-iron tanks at the bottom house the oscillatory circuits

Figure 2. Telemeter receiver

The indicating instrument is not shown

to the planes of the conductors. In a rotary variable air capacitor having two identical semicircular parallel fixed plates with a single semicircular rotor midway between them, a difference of potential causes several forces which are listed below. Figure 5 illustrates these forces and also shows the manner in which the two capacitors are formed by the stationary plates and damping disk of the primary instrument.

1. Forces between the rotor and upper stator which are balanced by forces between the rotor and lower stator. These forces, which are not shown on Figure 5, are parallel to the shaft and do not tend to rotate it.

2. Forces between the stator plates and the extended parts of the rotor, shaft, and so forth, which are symmetrical about the axis. These forces, shown as A_1, A_2, A_3, and A_4, are radial and do not tend to produce rotation.

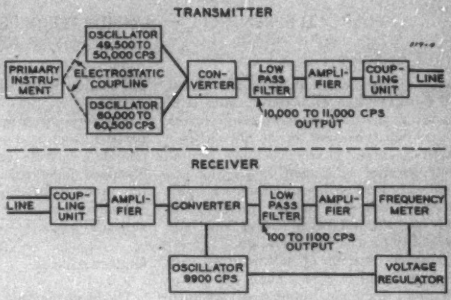
3. Forces between the diametrical edge of the rotor and the stators when the rotor is not fully meshed. These forces, shown as B_1, B_2, B_3, and B_4, are tangential and tend to turn the rotor in a direction that will mesh it deeper between the plates of the stator.

Thus, the only rotary electrostatic force is due to edge effect so that, with plates so shaped that the edge exposure is constant with any angle of rotation, the torque produced is dependent only on difference of potential and is entirely independent of angular position except near zero mesh and full mesh. Throughout practically the whole angle of rotation, the torque may be kept constant with constant applied potential. Currents flow radially and so do not produce any torque.

Two variable capacitors having a common rotor are incorporated in the transmitting instrument in such a manner that increasing the mesh of one capacitor decreases the mesh of the other. At the time that one capacitor is at maximum mesh the other is at minimum mesh so that the two oscillator frequencies approach or recede from each other with rotation of the common rotor. The two capacitors have a common rotor which is formed by the damping disk of the wattmeter. Each of the two stators consists of two parallel aluminum plates spaced 0.083 inch apart and mounted so the damping disk passes between them. The four plates are identical and have the same voltage applied between each plate and the rotor, thus neutralizing any torque which is produced.

Figure 3. Indicating instruments at the receiving end of six telemetering systems

Figure 4. Block diagram of the modulated-frequency system of telemetering



Since the two capacitors formed by the plates and damping disk are of small capacitance, the oscillator frequencies must be high in order to obtain the desired frequency change with a given angle of rotation of the instrument shaft. A fast response to changes in measured values is obtained since no mechanical connection is made to the shaft and all torques due to electrostatic forces are eliminated through cancellation.

Various oscillator frequencies can be used and, in the case of several metering sets operating over a common line, the frequencies must be separated sufficiently in order to provide the required number of channels. A remote-metering arrangement using typical oscillator frequencies will be described.

One of the variable capacitors described herein is in an oscillator circuit arranged to generate 50,000 cycles per second at minimum mesh of the capacitor plates and 49,500 cycles per second at maximum mesh. The other variable capacitor is in an oscillator circuit which generates 60,000 cycles per second at maximum mesh and 60,500 cycles per second at minimum mesh. At the time one capacitor is at maximum mesh the other is at minimum mesh so that the two oscillator frequencies approach or recede from each other with rotation of the transmitting instrument shaft. The oscillator tubes are A and B in Figure 6.

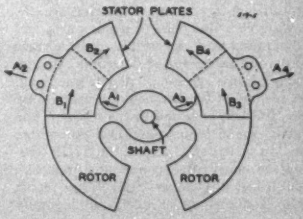


Figure 5. Electrostatic forces in two rotary variable air capacitors, each having two identical semicircular parallel fixed plates

A single semicircular rotor midway between the fixed plates is common to both capacitors

In order to insure an accuracy of two per cent, the maximum frequency variation of each of the three oscillators used in the system cannot vary more than two thirds of one per cent, assuming zero error in other components. Investigation showed that electron-coupled oscillators, tuned by a combination of positive- and negative-temperature-coefficient ceramic fixed capacitors plus a very small variable capacitor, have excellent stability over long periods of time. All oscillator circuits used in this system of telemetering are stabilized in this manner. The amount of negative-temperature-coefficient capacitor capacitance necessary to compensate for the coil and positive-temperature-coefficient capacitors in the set as described here was 10.71 per cent of the total capacity. Coils and mountings were developed that repeated their temperature-frequency characteristics faithfully.

The two voltages which are generated by the oscillators are fed into a converter

tube (tube *C* in Figure 6) where the difference or beat frequency, which varies between 10,000 and 11,000 cycles per second, is produced.

The output of the converter is fed into a low-pass filter which attenuates the high frequencies and all harmonics and passes only the beat frequency to an amplifier which is arranged in push-pull. In Figure 6 the amplifier tubes are *D* and *E*.

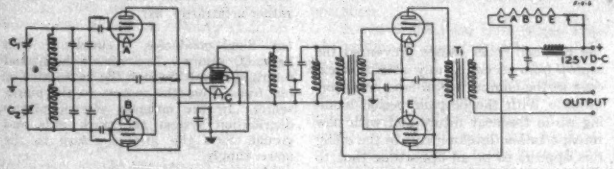


Figure 6. Schematic diagram of the telemeter transmitter

The amplifier feeds the line through an inductive coupling unit (T_1) which has laminated phenolic-sheet insulation between the primary and secondary windings and is capable of withstanding the highest voltage exposure of the line. A single-stage low-pass filter with a cutoff frequency of 4,500 cycles per second prevents the carrier power from entering the telephone instrument circuit where it would be wasted. This filter is not shown in Figure 6.

Receiver

The schematic diagram of the telemeter receiver is shown in Figure 7. At the receiving point the telephone line connects to a coupling unit similar to that at the transmitter. Voice frequencies are passed on to the telephone unit and the carrier frequency goes to the metering receiver.

The receiver consists of one 10,000 to 11,000-cycle amplifier stage, local oscillator, detector, low-pass filter, audio amplifier, frequency meter with indicating instrument, and a voltage regulator. The high-frequency amplifier stage (tube *A* and associated circuits) is fixed in frequency and is adjusted to 10,490 cycles per second. This frequency is approximately the geometric mean between 10,000 and 11,000 cycles per second. The local oscillator (tube *F*) has a constant output frequency of 9,900 cycles per second. The oscillator output and the high-frequency output are fed into the converter stage (tube *B*) where a beat frequency is produced. This beat frequency varies between 100 and 1,100 cycles per second. The high frequencies and all harmonics are eliminated by the low-pass filter which follows the converter stage. The output of the low-pass filter (100 to 1,100 cycles per second) is then amplified by the audio amplifier (tube *C*) which feeds the frequency meter. Incorporated as a part of the frequency meter is the final indicating instrument. Its pointer is at the left end of the scale with 100-cycle input and at the right end of the scale with 1,100-cycle input.

The frequency meter consists of two triode tubes, *D* and *E*, connected in series; that is, the plate of *E* is connected to the positive line, its cathode is connected to the plate of the other triode, *D*, and the other cathode is connected to the negative line. A fixed capacitor is shunted across the plate and cathode of each tube. These capacitors are shown as C_3 and C_4. The grids in normal operation are biased beyond cutoff so that no plate current flows except that due to a-c grid excitation. At the time one grid is made more positive, the other is made more negative so that both tubes cannot conduct at the same time. Both tubes may be nonconducting at once but conduction is alternate. When either tube becomes conducting, it discharges the capacitor across its plate-cathode circuit and charges the capacitor which is connected across the nonconducting tube. When the grid polarities change, the opposite capacitors charge and discharge. A d-c milliammeter in series with the d-c supply shows the average current used to charge the capacitors. With a constant direct voltage each charge requires a definite current for a definite time. The time of discharge and charge is shorter than the period of one input alternation at the highest frequency used and therefore the d-c milliammeter reading is a definite indication of the number of charges per second. The number of charges is controlled by the input frequency and is independent of the input voltage and wave form within wide limits.

The frequency meter and oscillator in the receiver are supplied from an electronic voltage regulator which is of a type frequently used and will not be described here. The neon-glow tube, *I*, and vacuum tubes *G* and *H* with their associated circuits comprise the voltage regulator. The actual output potential remains constant at 80 volts with the line voltage between 100 and 130.

Zero current in the indicating instrument puts the pointer off scale to the left. Such a condition indicates that the d-c power supply is off at the receiver or that the frequency-meter tubes have failed. If the transmitter power is off, or if the line is in trouble so that no carrier current is received, the bias is removed from the frequency-meter tubes and the indicating instrument goes off scale on the upper end. In this case the current is limited by degenerative resistors in the cathodes of the frequency-meter tubes. If the indicating instrument pointer is on its scale, the observer knows that none of the troubles just mentioned are being experienced.

Totalizing at the transmitter may be accomplished by a multiple-wound current transformer in the a-c circuits to the wattmeter. Totalizing at the receivers may be done in the frequency-meter output circuits by adding the direct current in a lead common to several instruments. Strip chart recording d-c milliammeters are available for continuous records at the receiving point.

Six complete sets of this system of telemetering are now in continuous service and have been for the past few years. The experience thus gained definitely indicates that the equipment has met the requirements expected of it. It provides almost instantaneous indications with standard accuracy. It permits a large number of readings to be transmitted over a single circuit and it is a simple matter to totalize readings from several transmitters. It is dependable and free from interference. It has proved easy to maintain at a minimum of expense.

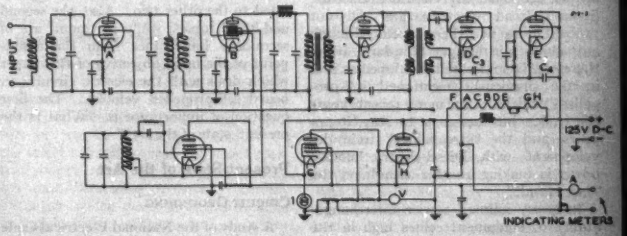


Figure 7. Schematic diagram of the telemeter receiver

Grounding of Circuits on Self-Propelled Vehicles

D. D. EWING
FELLOW AIEE

SOME years ago a prominent member of a group of engineers, who at that time called themselves "efficiency" engineers, had for a pet slogan the expression "whatever is, is wrong." For the present purpose any objections to this saying from the standpoint of syntax will be passed by but it has been observed that methods and procedures that for years have been refined in the crucible of practice usually have survived because they do have merit. Nevertheless the field of technology is anything but a quiescent one and it is desirable, therefore, that long existing methods, procedures, and standards be subject to constant scrutiny in the light of new developments.

For over 50 years the electric circuits and equipment on board electric railway cars have been in process of development and many of the electrical features of design and construction have long been pretty well standardized. For a similar period of time the electric circuits on automobiles have been undergoing a similar procedure and with a similar end result. At the turn of the century many enthusiastic electrical engineers believed that "the last stand" of the steam engine, namely, the steam locomotive, was about to be wiped out. Apparently these enthusiasts did not take into account all of the economic and technical factors. Steam-railroad electrification did not proceed apace and there developed much individuality in design. Standardization, therefore, is not as well developed as it is in the previously mentioned self-propelled vehicles. In more recent years the trolley bus has come to stay, it appears, and the "streamliner" train development with Diesel-electric motive power is making another assault on the "last stand."

In heavy railroad service interchangeability of equipment comes high in the list of the "must" requirements. A number of engineers have, for some years, been feeling that there should be a new scrutiny of existing electric-circuit and equipment standards and practices with the objective of setting up standards and recommended practices which, at least in the heavy transportation field, will further equipment interchangeability and promote efficient maintenance and repair methods and practices.

A few years ago a subcommittee of the committee on land transportation of the Institute was appointed to study this problem. A report was formulated but the war and other causes prevented the report from receiving any attention except in the committee on land transportation. With the postwar period looming up in the near future and with new transportation developments in the offing this appears to be an opportune time to discuss the problem again.

This paper is largely abstracted from the report of the subcommittee and the writer is indebted to the members of the subcommittee and the general committee for many of the ideas here presented. It is not expected that all engineers interested in the subject will agree with everything stated here. Frankly, it is hoped that they will not and that this paper will serve as a target to bring out constructive criticism and also new viewpoints so that in the end there may be some clarification and also some crystallization of the ideas now extant on the subject.

An analysis of the problems originally assigned to the subcommittee indicated that three topics were involved:

1. Grounding of circuits on vehicles.
2. Current leakage in self-propelled rubber-tired vehicles.
3. Static charges on vehicles.

The third topic is not necessarily related to the other two. Also, the second and third topics, while pertinent, are of secondary importance from the standpoint of the main objective of this paper which deals with the electric circuits on board self-propelled vehicles. The first question of importance is, "What is the present state of the art?"

Present State of the Art

Circuit Grounding

A study of the National Electrical Code and other safety regulations with reference to circuit grounding indicates that inside circuits are grounded to limit the voltage which may be impressed on a circuit by exposure to lightning; or by exposure to, or conflict with, higher voltage lines; or to limit the maximum potential to ground which may result from the normal operating voltage.

These limitations, which grounding is supposed to impose, are sought primarily in an endeavor to reduce the hazards from fire and electric shock or burn. A secondary objective is to minimize the hazards to service; for example, service interruptions. Also, circuits may be grounded to facilitate trouble indication and location, to provide for more accurate and reliable circuit protection, and, in some cases, to simplify the circuit layout and to allow a more economical construction.

The circuits which are used in self-propelled vehicles may be classified rather arbitrarily as:

(*a*). Single-conductor circuits with "ground" returns. In a vehicle the ground return is a path through the locomotive or bus frame from the motors to the power source. In the ordinary electric-railway distribution system the track rails and ground form the ground return to the power supply.

(*b*). Two-conductor circuits with both conductors insulated.

(*c*). Two-conductor circuits with one conductor grounded. The "ground" may be at one point or at several points. It may be a "dead" or solid ground, a ground through a resistance, a fuse or a protective relay of some sort, or through a combination of these components.

As used here the term "vehicles" includes electric locomotives, steam-electric locomotives, Diesel-electric locomotives, storage-battery locomotives, streetcars, electric motorcars, trolley busses, gas-electric busses, Diesel-electric busses and gas busses, and automobiles used in public transportation service. Also, the foregoing classification covers only d-c and single-phase a-c circuits.

In the selection of the proper circuit for a given service the engineer does not always have a free choice. For example, the power circuits of electric motorcars and locomotives which operate on rails and receive their power from an outside source ordinarily must use the class (*a*) circuit. Similarly, for practical reasons, the main circuits in a trolley bus must belong to class (*b*).

The choice is not so restricted, however, for the following circuits:

1. Traction motor circuits on steam-electric, Diesel-electric, and conversion-type electric locomotives.
2. Main power circuits on gas-electric and Diesel-electric busses and trucks.
3. Starting, lighting, and other auxiliary services on busses, trucks, and automobiles.
4. Auxiliary circuits on electric motorcars, locomotives, and trolley busses.
5. Electric circuits on railroad passenger cars.

This lack of restriction has resulted in a considerable diversity of opinion among

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D. D. Ewing is professor of electrical engineering, Purdue University, Lafayette, Ind.

engineers with a corresponding diversity of practice among equipment users. One user insists that all low-voltage circuits on self-propelled vehicles shall be ungrounded and another desires that his auxiliary equipment use the "ground-return" type of circuit. Many railroad passenger cars are lighted with a d-c axle-type generator and storage-battery system, other cars use three-phase 220-volt power service to operate their air conditioning apparatus. There is a discernible trend toward the use of even higher-voltage three-phase systems.

Common questions which arise are: Should the main power circuit on a Diesel-electric or gas-electric bus or locomotive be grounded or kept well insulated? If grounded, should the ground be a solid ground or a resistance ground? Should the circuit be grounded through a fuse or a relay? Should control, lighting, and other auxiliary services use grounded or ungrounded circuits?

These questions cannot be answered haphazardly. Often there is more than one good answer to a question. At any rate, the evidence available indicates that circuit design for self-propelled vehicles at present is not a universally standardized procedure.

In the selection of the proper circuit, the engineer should be guided by such considerations as safety, technical requirements, economy in first cost, and continuity of operation. Mostly the choice is, perforce, a compromise.

The outstanding advantages of the single-conductor ground-return system are simplicity of circuit layout, low first cost, and the quick detection and ease of location of faults. Its disadvantages are the lack of constancy in circuit resistance and the fact that a fault on the single conductor may render the circuit inoperative at some time when operation of some sort is absolutely necessary. Circuit-resistance variations are caused by loose rivets, bolts, joints, and so forth, in the mechanical parts. These poor contacts may result in burning and corrosion of the metal frames and leakage through bearings may cause serious bearing trouble.

In automotive equipment this circuit is used almost universally and the apparatus and accessories necessary in its application are highly developed and very economical in cost.

The system of employing two insulated conductors has the advantage of making possible a high degree of circuit insulation and isolation. It is practically the only choice for all circuits fed by trolley voltage in the trolley bus. Circuit resistance is easy to maintain at a constant level and the likelihood of failure is less since there must be a fault on each line before complete circuit failure can occur. This advantage becomes a real disadvantage, however, when the matters of fault indication and location are considered. This circuit costs more and there seems to be a trend toward its increased use in the better class of vehicles. In some services, where a common return wire is used, the insulated circuit is at a disadvantage as compared with the ground-return circuit. This is notably true in the case of certain control and signal circuits where an opening in the common return wire might cause false indications or false operation.

Circuits of the third class (those with two conductors, one of which is grounded) have a wide field of application, potentially at least. They are high in first cost and maintenance but provide current paths of constant resistance and a ready means of fault indication and location. Such circuits appear to be particularly applicable to the traction motor circuits on a-c and Diesel-electric locomotives and, in general, wherever a circuit path of high integrity is required.

The preceding discussion applies only to d-c and single-phase services.

The heavy power demands on modern railway trains have resulted in the installation of three-phase generating units on some trains. Voltages up to 220 volts are in use and higher voltages have been given some consideration. The circuits used require a minimum of three conductors. As the 220-volt three-phase circuits used for supplying the air conditioning apparatus on some railway passenger cars must be operated from the standby power services in the yards, grounding of the circuits on the cars is not feasible because of the possibility of neutral or other grounds on standby services. Where the 220 volts is transformed within the car to some lower voltage for lighting or other low-voltage service it seems to be customary to ground one side of the low-voltage service.

Current Leakage in Self-Propelled Rubber-Tired Vehicles

A number of years ago, when someone took some streetcars off the tracks and mounted them on wheels suitable for operation over street pavements, a new sort of trouble developed. People on the street sometimes received severe electric shocks when they stepped aboard the new "trackless trolleys." Circuit insulation which never gave any trouble in the old single-conductor ground-return streetcar circuits developed electrical leaks. The early equipment was adapted streetcar equipment and was not suitable for use on a vehicle where the body could not be solidly grounded. Considerable investigation was done on this problem by equipment users and manufacturers as well as by the American Transit Engineering Association and its predecessor organization. It was found that if all circuits, power and auxiliary, were very carefully insulated from the bus body, "hot" body trouble was no longer a major worry. Busses gave little or no trouble from current leakage when insulated to meet specifications[3] calling for the following minimum insulation resistances:

1. Power circuits (without motors) in parallel with other circuits ..... 8 megohms
2. Individual motors ..... 10 megohms
3. Assembled control apparatus ..... 5 megohms

One operator tries to maintain at all times the bus-body-to-trolley resistance greater than three megohms.

Procedures for the mitigation of current leakage troubles have also included, in some cases, the use of insulated steps, door handles, stanchions, and grab handles.

All in all, the problems that arise from current leakage are so well in hand that the subject would not have been discussed here were it not for the fact that current leakage is often blamed for shocks that have a very different cause; namely, static charges.

Static Charges

In modern busses and automobiles static charges have been the source of no little trouble under certain atmospheric conditions. Present-day upholstery materials and modes in wearing apparel have combined to accentuate the difficulty.

The electron theory has afforded the physicists an easy explanation of the accumulation of static charges. These charges are often spoken of as frictional electricity although friction itself seems to have little to do with the matter. When two dissimilar materials such as wool and rubber or silk and glass are pressed tightly together or are rubbed together some of the electrons stray from one material to the other. For example, electrons will stray from the wool to the rubber leaving the wool positively charged and the rubber with a negative charge. When silk and glass come in contact some electrons leave the glass and go to the silk so that the glass becomes positively charged and the silk negative. Charges so produced are common causes of trouble in printing presses, grain elevators, textile elevators, textile mills, moving belts, gasoline filling stations, and so forth.

As far as vehicles are concerned, two types of trouble are encountered. These may be arbitrarily designated as "inside" and "outside" troubles.

The modern seat cushion with a mohair or woolen-cloth cover and a rubber-cushion filling becomes really quite an ideal electrostatic generator when someone with rubber-soled shoes sits on the cushion. The passenger's body rapidly acquires a positive charge by conduction from the seat cushion if the air is dry enough to prevent leakage of the charge. When the passenger touches the signal button to indicate his stopping place, he receives a shock which he is quite likely to attribute to the signal circuit. The shock is identical to the one the passenger

would receive in his own home if, after walking over a woolen carpet or waxed floor, he should happen to touch a metal object. Other causes of "inside" shock are scuffing of feet on rubber floor mattings and sliding on rubber-fabric seat coverings. These shocks are not in themselves dangerous but they may cause passengers to injure themselves in some other way. There seems to be no easy way of mitigating this trouble. Proper combinations in upholstery and the covering of all metal objects easily accessible to passengers afford some relief. Fortunately, meteorological conditions are only occasionally favorable to the production of static charges.

"Outside" shocks are those received by persons standing on the pavement and touching the vehicle body. The bus body is insulated from the earth by rubber tires and in some cases by the paving, as, for instance, dry concrete or asphalt. A charge may accumulate on the vehicle body by the body moving through the air or as a result of the wheels running over dry pavement. As the bus body is a rather large capacitor, a charge of considerable magnitude may be collected. When a person who is standing on the ground touches the car body there is a discharge which may produce quite a shock. These charges are never bothersome except in dry, frosty weather or at times when both air and pavement are very dry. Busses running on gravel roads have very little trouble with them. They are worst on asphalt-covered streets and with new or cleanly washed tires. Dirty tires help conduct the accumulated charges to earth. This process can be furthered by painting the inner sides of the tires with some form of conducting paint. Recent improvements in the way of "conducting" tires undoubtedly will be available after the war. Keeping the wheels perfectly aligned so as to avoid the slippage of rubber over asphalt is helpful. Some companies use drag chains or some similar devices during periods when static is troublesome. Some simple means of discharging the static charges as fast as they are developed is needed. Possibly the development of new surfacing materials will be hastened by the war effort. In any event the problem is a complex one and needs much further study.

Conclusions

Giving due consideration to matters of economy, circuit requirements from a power standpoint, and to the reasons underlying circuit grounding, the following conclusions may be drawn:

1. All circuits on trolley busses which operate at trolley potential must be of the two-conductor type with all wires and apparatus well insulated from the bus body and other parts accessible to passengers or street traffic.

2. All low-voltage circuits on small busses and automobiles used in passenger service may be of the one-insulated-conductor ground-return type.

3. All circuits carrying small currents at low voltages (6 to 32 volts) which are thoroughly isolated from possible exposure to, or conflict with, higher voltages and which are accessible in any way to passengers or street traffic may be of the one-insulated-conductor ground-return type.

4. Ground-return circuits should not be used on trucks or other vehicles carrying gasoline, oil, or other highly inflammable or explosive materials.

5. All so-called "ground-return" circuits, where there is possibility of a loose mechanical joint in part of the return circuit, should have the return of bare copper conductors electrically connected to the mechanical parts at a number of points.

6. All internal circuits carrying heavy currents at both low and high voltages (starter-motor circuits on automobiles and small busses excepted) may be of the two-insulated-conductor type with one conductor grounded. The two conductors here serve as a guarantee of circuit integrity and the ground connection is of assistance in fault indication and location, keeps static charges drained off, and otherwise assists in protecting apparatus and service. This classification is not intended to include circuits which are fed from an external source such as a trolley wire or third rail.

7. All circuits on rail vehicles connected to external sources of power such as trolley wires and third rails are necessarily of the one-conductor-with-ground-return type or of the two-conductor-with-one-conductor-grounded type.

8. Control and signal circuits using a common return wire may have this common return grounded on car or truck frames at a number of points whenever other circuit conditions are such as to permit grounding. The grounding of the common return will tend to reduce false indications or operations in case of return-wire breakage.

9. Three-phase 220-volt circuits used on railroad cars to supply air-conditioning equipment should not be grounded. However, the structural parts of the cars should be solidly grounded.

10. All a-c and d-c circuits on railroad cars with voltage ratings of 64 to 120 volts should be of the insulated-conductor type. If an a-c circuit is fed through a transformer from a higher-voltage circuit then the lower-voltage circuit should have one conductor grounded. Also, if such a circuit is exposed to static from belts or moving air streams, one side of the circuit should be grounded.

It does not seem feasible to make a complete classification of all the circuits used in vehicular service and categorically state that such and such circuits should always be grounded and certain others should not be. The safety, economic, and technical factors are somewhat different in the different transportation fields, and these factors should be given some weight in the consideration of any recommendations relative to standardization.

Recommendation

Standards in some of the operating fields have been set up by the American Association of Railroads, in others by the Society of Automotive Engineers, and in still others by the American Transit Association. In those fields where these several associations have what for convenience may be called primary jurisdiction, the standardization problems have on the whole been cared for promptly and effectively. Under present conditions there is a considerable amount of overlapping. For example, the power equipment on a Diesel-electric locomotive from one viewpoint may be considered as just overgrown Diesel-electric bus equipment. The question arises as to who shall set up the needed equipment standards in such a case? Shall they be set up by manufacturer's associations, by professional engineering groups, or associations of operating companies? The question is a difficult one. Obviously some things belong in one place and some in another. In this case it is possible that better end results will be produced if the work is done by joint committees working under the sponsorship of a professional engineering group. It would seem to be a proper recommendation, therefore, that the Institute act as sponsor in this instance and set up the necessary mechanism for working out the desired standards and recommended practices.

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Determination of Transient Shaft Torques in Turbine Generators by Means of the Electrical–Mechanical Analogy

G. D. McCANN
MEMBER AIEE

C. E. WARREN
ASSOCIATE AIEE

H. E. CRINER
NONMEMBER AIEE

Synopsis: A brief description is given of the mechanical-transients analyzer and its application to the determination of the shaft torques in turbine generators during transient disturbances, such as electric short circuits and synchronizing out of phase. This device employs the principle of the electrical–mechanical analogy with analogous electric circuits to represent a given mechanical system and special electric circuits for producing the desired transient excitation functions. With the analyzer a detailed study has been made of the shaft torques that can occur in turbogenerators with mechanical systems having both one and two modes of vibration. The relative severity of various types of faults has been determined together with the effect of external system or fault resistance and generator loading. Short circuits produce rotor air-gap torques containing damped unidirectional, fundamental electrical frequency, and second-harmonic frequency components. In the practical range of machine design, the fundamental-frequency component has the dominant effect on the resulting transient shaft torques for the more severe types of disturbances. The types of short circuits studied include three-phase, line-to-line, single-line-to-ground, and double-line-to-ground faults from no load and full load and with varying amounts of external resistance. It was found that for short circuits at no load with no external resistance a line-to-line fault results in the most severe shaft torques. For faults with low external resistance (of the order of one per cent per phase), a double-line-to-ground fault produces the highest shaft torques which for mechanical systems of low natural frequency may exceed the torques produced by a line-to-line fault with zero resistance. However, for values of external resistance as high as the machine subtransient reactance, the shaft torques are lower than with zero resistance. The most severe fault torques are produced by line-to-line short circuits from full load with no external impedance. Synchronization at angles greater than 30 degrees can produce transient shaft torques which in some cases are more severe than those resulting from short circuits.

THE determination of transient shaft torques in turbogenerators during short circuit or synchronization out of phase is representative of a large group of problems encountered in the design of mechanical or electromechanical apparatus. Stated in general terms, the problem is to determine the transient response of a physical system to a suddenly applied excitation. In a large majority of the cases which arise, the motion of the system can be specified, with sufficient accuracy, by a set of linear constant-coefficient differential equations. The solution of these equations, by classical or operational methods, is well known and does not present any difficulties of a theoretical nature. However, if the system being studied contains two or more degrees of freedom and the suddenly applied excitation is at all complicated, the work involved in the numerical solution of the equations of motion soon becomes prohibitive. Under these conditions it becomes highly desirable to seek other means of solution. Several methods are available. These include mechanical calculators, such as the differential analyzer, measurements on full-scale models, or some equivalent dynamic system. This may be a simplified equivalent mechanical system or its analogous electric circuits.

Table I. Electrical–Mechanical Analogy Used With Mechanical-Transients Analyzer for the Study of Turbine-Generator Shaft-Torque Problems

Inertia–Inductance Torque–Voltage Analogy

Inertia (I)	Inductance (L)
Torque = inertia × angular acceleration	Voltage = $L\frac{di}{dt}$
$T = I\frac{d\omega}{dt}$	
Spring constant (K)	Capacitance (C)
T = K × angular displacement	$V = \frac{q}{C} = \frac{1}{C}\int i\,dt$
$T = K\theta = K\int\omega dt$	
Velocity damping (G)	Resistance (R)
$T = G\omega$	$V = Ri$

The method of the electrical–mechanical analogy is particularly well suited for solving problems of this nature. The analogy between electric and mechanical systems has been well known for many years[1] and is based on the identity in the form of the differential equations representing the two systems. The particular analogy used in this paper is given in Table I. This is classified as the inertia–inductance torque–voltage analogy. This is not the only one possible. For example, the dual of the afore-mentioned circuit may be used in which inertia and capacitance are analogous quantities, and torque may be analogous to current. The inertia–inductance analogy and its dual represent the two possible analogies between the physical constants of the electric and mechanical systems for each of which there is an infinite number of possible analogies between the electrical and mechanical variables. For example, in the inertia–inductance analogy torque may be analogous to voltage, rate of change of voltage, and so forth; while in the inertia–capacitance analogy torque may be analogous to current, rate of change of current, and so forth. The significance of these analogies is discussed in greater detail in reference 2.

It is evident from the foregoing discussion that the complex cumbersome mechanical system may be replaced by its analogous electric circuit consisting of simple inductors, capacitors, and resistors. The required excitation is applied to the analogous electric system by means of special electric circuits, and the transient response is measured directly as voltages and currents. This method has the advantages of simplicity, low cost, and flexibility. A new device, the mechanical-transients analyzer, has been developed[2] for solving a wide range of transient vibration problems by this means.

Nature of the Transient Short-Circuit Torque Problem

When a generator is suddenly short-circuited or synchronized out of phase, a transient torque consisting of unidirectional and alternating components suddenly is impressed on the generator rotor. Each component of this torque decays exponentially to a value determined by the steady-state terminal conditions of the machine. In the case of a salient-pole generator, there is an infinite series of alternating components at harmonic electrical frequencies; whereas, for the turbogenerator, the only alternating torques of appreciable magnitude are those at fundamental and second-harmonic electrical frequencies. Equations for the calculation of these torques for a turbogenerator under various terminal conditions are given in a companion paper.[3] A simplified form of the rotor air-gap torque for turbogenerators is illustrated by the following equation:

$$T_r = Ae^{-at} + Be^{-bt}\sin\omega t - Ce^{-ct}\sin 2\omega t \quad (1)$$

A typical turbogenerator on which these electrical torques are impressed is shown by the tandem unit at the top of

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G. D. McCANN, C. E. WARREN, and H. E. CRINER all are with Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.; Doctor McCann is transmission engineer, central-station engineering department, and Mr. Warren is in the industry engineering department.

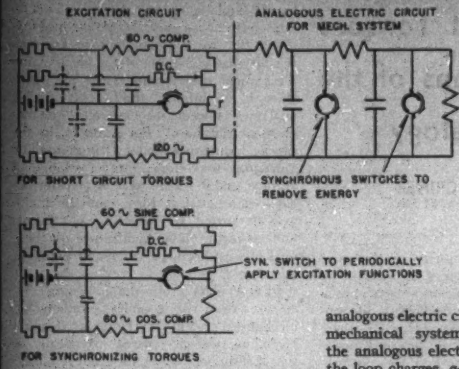


Figure 1. Simplified circuit diagrams of the mechanical-transients analyzer as used for determining turbine-generator shaft torques

Figure 3A. The mechanical constants of this system are the inertias of the generator and turbine rotors (I_1, I_2, I_3), the spring constants of the generator and turbine shafts (k_1, k_2) and equivalent velocity-damping factors, resulting largely from hysteresis loss in the shaft materials and energy absorption in couplings, bearings, and fits. As a result of the suddenly impressed rotor air-gap torque (T_r) the mechanical system will oscillate at forced and natural frequencies producing abnormal torques in the generator and turbine shafts. A knowledge of the peak shaft torques resulting from these oscillations is desirable in the design of the shafts and their associated couplings and keyways. The equations of motion for the mechanical system, for the generator load torque T_L with no mechanical damping assumed, are the following:

$$\left.\begin{aligned} T_r-\Delta T_L &= I_1\ddot{\theta}_1+k_1(\theta_1-\theta_2)\\ 0 &= k_1(\theta_2-\theta_1)+I_2\ddot{\theta}_2+k_2(\theta_2-\theta_3)\\ 0 &= k_2(\theta_3-\theta_2)+I_3\ddot{\theta}_3 \end{aligned}\right\} \quad (2)$$

The angular displacements (θ) of the respective rotors are measured from the average position of the rotors at $t=0$; that is, the constant velocity of rotation does not appear in the equations. The quantity ΔT_L is the change in load due to the terminal fault on the machine. The change in load depends on the type of fault and other system conditions. It is usually assumed that this change in load takes place instantly on occurrence of the fault. The actual torque on each shaft is then the torque as determined from the preceding equations plus the initial torque on the shaft at $t=0$.

Analogous Electric System

A simplified circuit diagram of the mechanical-transients analyzer as used for the solution of the foregoing problem is shown in Figure 1. The two principal parts of the analyzer are the excitation circuits, which produce the voltages proportional to the components of T_r, and the analogous electric circuits representing the mechanical system. The equations of the analogous electric circuit in terms of the loop charges, q_1, q_2, and q_3, are as follows:

$$\left.\begin{aligned} E_r-\Delta E_L &= L\ddot{q}_1+\frac{1}{C_1}(q_1-q_2)\\ 0 &= \frac{1}{C_1}(q_2-q_1)+L_2\ddot{q}_2+\frac{1}{C_2}(q_2-q_3)\\ 0 &= \frac{1}{C_2}(q_3-q_2)+L_3\ddot{q}_3 \end{aligned}\right\} \quad (3)$$

where E_r is a voltage whose components are analogous to the components of T_r and ΔE_L is analogous to the change in load ΔT_L. A comparison of equations 2 and 3 shows immediately the similarity of the equations of motion of the two systems, which is the basis of the analogy.

The voltage E_r is generated in the resistor r connected across the terminals of the analogous circuit. The various components of E_r are produced as follows. The unidirectional or d-c component results from the discharge of a capacitor through a resistor. The capacitor shown in the d-c circuit is charged by a constant-voltage source and is then discharged through a portion of r when the rotating switch closes. The capacitor recharges during the time the switch is open and the cycle is repeated when the switch again closes. By driving the switches at synchronous speed, the voltages may be viewed as a standing image on the screen of a cathode-ray oscillograph. This is a method that was developed for studying transients in electric power systems.[4] The alternating components of torque are generated in a similar manner, except that the capacitors are discharged through an inductor and resistor in series. The resulting oscillatory current will be a damped sinusoidal wave, and the voltage drop across r will be analogous to the damped sinusoidal components in T_r. By adjusting the capacitance, inductance, and resistance in this circuit, any desired frequency and damping may be obtained. Components of opposite polarity are obtained by discharging through the lower section of r. When it is desired to obtain a damped cosine function of time, the resistor r is replaced by a small inductor (see lower half of Figure 1). The voltage across this inductor will be a cosine function provided its losses are low. However, it is always possible to balance out the inphase component of the inductor by an inphase component of opposite polarity.

It is necessary that the currents in the analogous circuit produce no appreciable voltage across the coupling resistor r or coupling inductor. The current in the excitation circuits must be very large compared to the current in the analogous circuit that flows through r. This condition will be satisfied provided the coupling impedance is at all times small compared to the impedance looking in at the terminals of the analogous circuit. Since the analogous circuit always contains a slight amount of resistance, which represents the damping of the mechanical system, it is possible to make r sufficiently small so that the foregoing conditions are satisfied, even though the analogous circuit may be resonant at the frequency of the excitation circuit. This has been proved experimentally by measuring the voltage drop across r as the analogous circuit was made to approach resonance.

As discussed in detail in reference 2, special inductors were developed for the analogous circuits of the mechanical-transients analyzer so that the circuits provide damping as low as that found in practical mechanical systems. These coils have a Q in excess of 100 in the range of 200 to

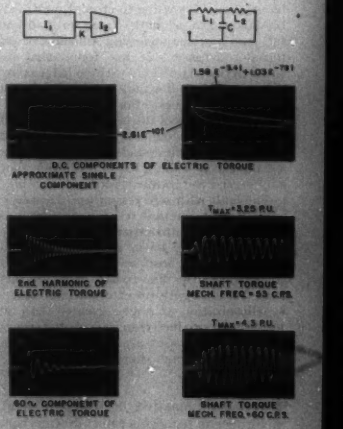
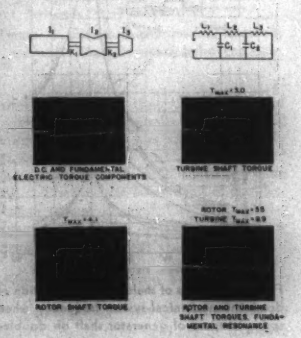

D.C. COMPONENTS OF ELECTRIC TORQUE
APPROXIMATE SINGLE COMPONENT
2nd. HARMONIC OF ELECTRIC TORQUE
SHAFT TORQUE MECH. FREQ. = 53 C.P.S.
60 ∿ COMPONENT OF ELECTRIC TORQUE
SHAFT TORQUE MECH. FREQ. = 60 C.P.S.

Figure 2. Mechanical-transients-analyzer oscillograms of rotor air-gap torques and resulting shaft torques on single-frequency turbo-generator unit for line-to-line short circuit from no load

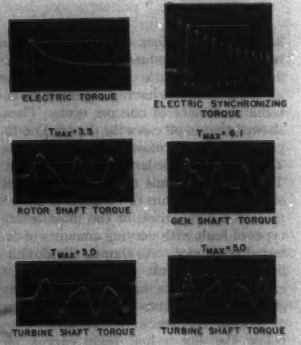
$R_a=1$ per cent per phase
$l_1=1$; $l_3=0.16$; $K=1.54\times10^4$

1,000 cycles per second, which corresponds to an amplitude decay factor of less than three per cent per cycle. An illustration of the effect of Q on the crest per unit torque is illustrated by Figure 5. It should be noted that the peak torque is changed by only 8.5 per cent with a Q variation of 100 to 50 (respective decrements three and seven per cent) in the region of resonance and that the effect of the Q change is entirely negligible in the practical range of mechanical-system frequency.

The required relationships between the dynamic constants of the mechanical system and the electrical constants of the analogue are given in reference 2.


D.C. AND FUNDAMENTAL ELECTRIC TORQUE COMPONENTS
TURBINE SHAFT TORQUE
ROTOR SHAFT TORQUE
ROTOR AND TURBINE SHAFT TORQUES, FUNDAMENTAL RESONANCE

A. Three-phase short circuit from no load with no external resistance



B. Three-phase short circuit from no load
$R_s = X_d''$ per phase

C. Synchronizing 90 degrees out of phase
System reactance $X_s = X_d''$

Figure 3. Mechanical-transients-analyzer oscillograms of rotor air-gap and shaft torques on double-frequency turbogenerator unit

$I_1 = 1$ $K_1 = 1.35 \times 10^4$
$I_2 = 0.821$ $K_2 = 1.09 \times 10^4$
$I_3 = 0.821$

Mechanical Systems and Types of Disturbances Studied

The wide variation of possible mechanical-system constants and types of short circuits and synchronizing torques makes it impractical to present a completely comprehensive analysis of this problem. However, general conclusions can be drawn with regard to certain factors, such as the relative severity of various types of faults and the effect of external impedance and generator load. With these as a basis the mechanical-transients analyzer provides a ready means of studying a given unit for the particular system condition under which it is to operate.

Two types of units were chosen for detailed study, a single-frequency unit consisting of a generator and one turbine element and a double-frequency unit with a generator and two turbine elements. The dynamic mechanical systems and their analogous electric circuits for the mechanical-transients analyzer are shown in Figures 2 and 3A. The same generator was assumed for both units. Its electrical constants are listed at the bottom of Table II, which also gives the equations for the types of short circuits and synchronizing torques studied. The derivation of these equations is presented in a companion paper.[1] The electrical constants of the assumed machine result in air-gap torques which are representative of the upper range of severity.

Typical Torque Oscillograms

In Figures 2 to 4 are shown typical oscillograms of the rotor air-gap torques and the resulting shaft torques obtained with the mechanical-transients analyzer. Figures 2 and 3 apply to the two units chosen for detailed study. Figure 4 illustrates the use of the analyzer for more complex problems. In this system two generators are driven by a geared turbine. The generator being short-circuited has salient poles, and the air-gap torque consists of a damped unidirectional component and a series of damped sinusoidal components of fundamental and harmonic electrical frequencies. However, the effects of all components above the fourth harmonic are negligible. The equation for the air-gap torque as used with the analyzer is given in the caption of Figure 4.

Torque-Frequency Curves

For the two units chosen for detailed study fixed relationships between the various inertia constants were assumed and the effect of varying the shaft spring constants determined. In this way curves were obtained of the maximum shaft torques resulting from each type of disturbance. Such curves provide a complete analysis of the dynamic mechanical system of a single-frequency unit, because for such a system

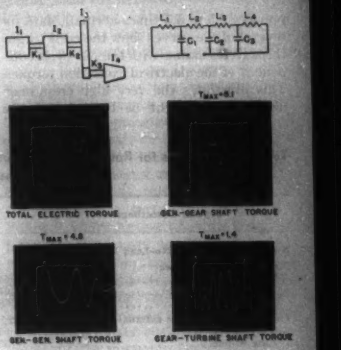


Figure 4. Typical gear-driven-generator problem

Three-phase short circuit on salient-pole generator from no load with no external resistance
$T_r = \epsilon^{-4.5t}(6.2 \sin \omega t + 4.65 \sin 3\omega t) - \epsilon^{-3t}(2.13 \sin 2\omega t + 1.95 \sin 4\omega t) + 1.2\epsilon^{-2t}$
Fundamental frequency is 25 cycles per second

$I_3 = 1$ $K_1 = 1.065 \times 10^4$
$I_1 = 0.965$ $K_3 = 3.72 \times 10^4$
$I_2 = 1.45$ $K_2 = 18.22 \times 10^4$
$I_4 = 2.52$

the torques resulting from a given disturbance are a function only of the mechanical-system frequency and the ratio of the two inertia constants. The resulting crest torque for a given system frequency is directly proportional to the ratio $I_3/(I_1+I_2)$. Thus for a given electrical torque, the crest-torque curves for the single-frequency unit studied (Figures 5 and 7) therefore can be applied to any other single-frequency unit by proper adjustment of the torque magnitudes. However, for the double-frequency unit the larger number of system elements makes it impractical to present a general analysis of all possible systems. For this case it was found that the more important conclusions can be illustrated by a single set of curves of crest torque plotted as a function of the dominant one of the two system frequencies: that is, the frequency containing most of the mechanical energy. The curves for this unit were obtained by varying the spring constant of only one shaft (the generator-turbine shaft). For this condition the less important system frequency ranged between 12 and 22 cycles per second. Crest-torque curves as obtained in this manner are given in Figures 6 and 8. It should be realized that the magnitudes of the crest torques shown on these curves do not apply to all designs, since absolute magnitude is a function of the relation between the various inertia constants.

Although as shown by the curves the practical design range should place the dominant natural frequency appreciably below 60-cycle resonance (usual design

practice 2.5 to 6.5 times normal), data for several of the curves show the crest torque through resonance with the 120-cycle component of the electrical excitation torques. This illustrates the very high crest magnitudes that might be built up if the expected that the line-to-line fault would produce the most severe shaft torque, since it has both the highest d-c and 60-cycle components of the air-gap torque. In the practical range of system frequencies the effect of its larger negative

Table II. Equations for Rotor Air-Gap Short Circuit and Synchronizing Torques as Used for Transient-Shaft-Torque Study

Type of Disturbance	Per Unit Rotor Air-Gap Torque
Short Circuits From No-Load Rated Voltage	
No external impedance:	
Three-phase	$1.54e^{-7.5t}+10.3e^{-10t}\sin \omega t$
Line-to-line	$2.07e^{-6.5t}+10.4e^{-6.5t}\sin \omega t-5.18e^{-6.7}\sin 2\omega t$
Line-to-ground	$1.88e^{-7.5t}+9.50e^{-6.5t}\sin \omega t-4.75e^{-6.5t}\sin 2\omega t$
One per cent per phase external resistance (R_a) — zero external reactance:	
Three-phase	$2.60e^{-10t}+10.3e^{-10t}\sin \omega t$
Line-to-line	$1.58e^{-6.4t}+1.03e^{-10t}+10.4e^{-10t}\sin \omega t-5.18e^{-6.7t}\sin 2\omega t$
or	$2.61e^{-10t}+10.4e^{-10t}\sin \omega t-5.18e^{-6.7t}\sin 2\omega t$
Line-to-ground	$2.55e^{-9.3t}+9.50e^{-6.5t}\sin \omega t-4.75e^{-6.5t}\sin 2\omega t$
Double-line-to-ground	$3.16e^{-10t}+10.4e^{-10t}\sin \omega t-1.39e^{-6.5t}\sin 2\omega t$
External resistance = X_d'' per phase—zero external reactance:	
Three-phase	$5.19(e^{-10t}-e^{-14.1t})+5.19e^{-10t}\sin \omega t$
Synchronizing Torque at Rated Voltage	
Three phase 90 degrees out of phase	$5.16+5.16\sin \omega t-5.16\cos \omega t$
System reactance $X_s = X_d''$	

Per Unit Electric-Machine Constants

X_d''	X_d'	X_d	X_1	X_0	T_{do}''	T_{do}'	R_1	R_2	R_a
0.097	0.153	1.17	0.096	0.0177	0.055 second	6.65 second	0.0048	0.025	0.00105

natural frequencies were allowed to approach resonance with the excitation frequencies.

Short Circuits at No Load—No External Impedance

Figure 5 gives the crest torque on the single-frequency unit resulting from three types of fault at no-load rated voltage and with no external impedance. Figure 6 gives the effect of the various components of the electrical excitation torque for a line-to-line fault on the double-frequency unit. As shown by Table II, it would be

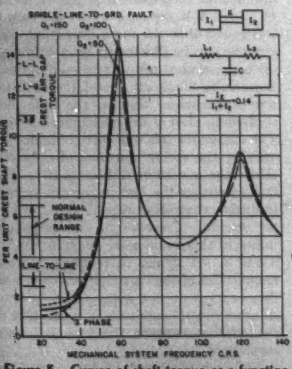


Figure 5. Curves of shaft torque as a function of mechanical-system frequency for short circuits on single-frequency unit from no load and with no external resistance

120-cycle component should not be important. This is borne out by the solutions. As illustrated in Figure 6, the 60-cycle component of the rotor air-gap torque has the dominant effect upon the crest shaft torque, except at the lower range of mechanical-system frequencies. Although the variation of crest shaft torque is not very great for the three types of faults (see Figure 5), the line-to-line fault gives the most severe condition when no external impedance is present.

Effect of External Resistance

The presence of external-system reactance decreases the magnitude of the fault currents and, therefore, the rotor air-gap torque. However, the addition of external resistance without increasing the reactance (which may occur for certain types of faults with appreciable resistance) can increase some components of the air-gap torque The effect of external resistance on the rotor air-gap torques is shown on Table II. It increases the crest magnitude of the d-c component, increases rapidly the damping of the 60-cycle component, and increases more slowly the damping of the d-c component. This can readily be seen by comparison of the electrical-torque oscillograms in Figures 2 and 3A. Also (as shown by Table I of reference 3), the relative magnitude of the more highly damped of the two decrement factors of the d-c component is increased so that a less accurate representation is obtainable with only one equivalent decrement factor. However, this latter factor is not important for small values of external resistance. Representative solutions (see Figure 2) were obtained, using the two forms of the d-c component listed in Table II for a line-to-line fault with one per cent per phase external resistance. No appreciable difference was found in the resulting shaft torques.

Since the addition of external resistance increases the magnitude of the d-c component of electrical torque, it might be thought that such a condition will produce more severe shaft torques at the lower system frequencies where the d-c component

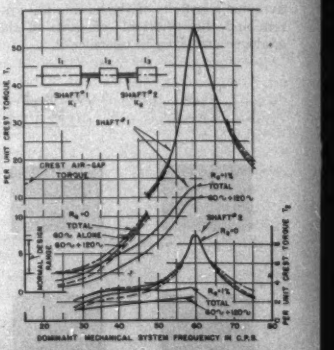


Figure 6. Curves of shaft torque as function of dominant mechanical-system frequency when spring constant of generator shaft on double-frequency unit is varied

Line-to-line faults from no load
$I_1=1;\ I_2=I_3=0.821;\ K_2=1.09\times10^4$

has its greatest effect. This was found to be true for low values of external resistance. Torque data were obtained for all types of faults having a per phase external resistance of one per cent. These showed that in all cases the double-line-to-ground fault is most severe since (see Table II) it has the largest d-c component Typical crest-torque curves for this case are given in Figure 6. Figures 7 and 8 present a comparison of the most severe types of fault with varying amounts of external resistance. As shown, the double-line-to-ground fault with one per cent external resistance can produce slightly greater crest torques at the lower range of system frequency but rapidly drops below the line-to-line fault curves for no external resistance as 60-cycle resonance is approached.

To show that the further increase of the d-c component with greater amounts of external resistance is more than offset by increased damping, torque curves were obtained for the case of a three-phase fault with the per phase external resistance equal to (X_d''). These are shown in Figures 7 and 8. For this case the resistance is sufficiently large to affect materially the fault currents and machine

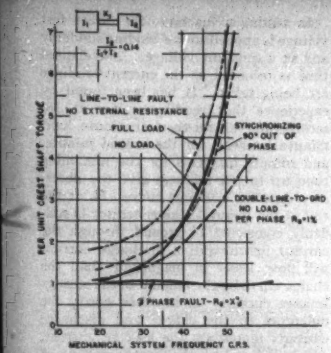


Figure 7. Shaft-torque—mechanical-frequency curves for single-frequency turbogenerator

time constants so that the equations of reference 3 do not apply. The electrical torque for this case was calculated directly from fundamental machine equations.[6] A solution for this case is shown in Figure 3B. The 60-cycle component of the electrical torque is negligible, and the d-c component is the difference of two exponentials (see Table II).

Short Circuits From Full Load

The transient rotor air-gap torques for short circuits from load are of the same form as those from no load (T_r) with the addition of a transient term (ΔT_L) to represent the rapid dropping of part of the load (see equation 2). The total shaft torque is the transient response torque to these excitation functions as determined with the mechanical-transients analyzer plus the initial steady-state load torque. The transient-torque components (T_r) are very nearly proportional to the square of the voltage behind subtransient reactance. For this machine at unity power factor these components are only about one per cent higher than for short circuits from no load. The most severe shaft torques for this machine are produced by a short circuit from unity power factor at full load. It is difficult to determine in general the form of the component representing dropping of load, since this is affected by such factors as electric-system conditions and fault impedance. To simplify this problem it was assumed that the load is suddenly dropped. Total load was assumed to be dropped for three-phase and double-line-to-ground faults and half load for line-to-line and single-line-to-ground faults. Both turbine elements of the double-frequency unit were assumed to have equal outputs so that the turbine–turbine shaft carries half the steady-state load. For the foregoing assumptions the most severe shaft torques are produced by line-to-line faults from full load with no external resistance. Curves for the crest torques resulting from such a fault are shown in Figures 7 and 8. These are about one per unit higher than the corresponding fault from no load, showing that the effect of the negative component representing dropping of load is not very great and a more detailed treatment of the manner of dropping load is not too important.

It might be thought that a high-resistance fault from full load could be more severe if the external resistance is high enough actually to increase the machine load. Then the added load-changing component will be positive. However,

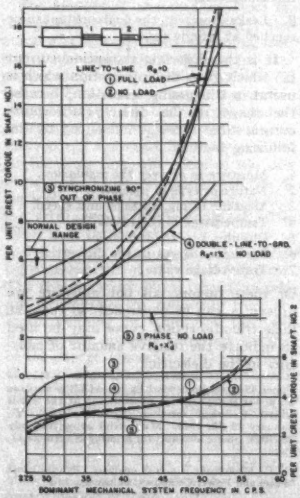

LINE-TO-LINE R_e=0
① FULL LOAD
② NO LOAD
③ SYNCHRONIZING 90° OUT OF PHASE
④ DOUBLE-LINE-TO-GRD. R_e=1% NO LOAD
⑤ 3 PHASE NO LOAD R_e=X_d''
NORMAL DESIGN RANGE
PER UNIT CREST TORQUE IN SHAFT NO.1
PER UNIT CREST TORQUE IN SHAFT NO.2
DOMINANT MECHANICAL SYSTEM FREQUENCY IN C.P.S.

Figure 8. Shaft-torque—dominant-mechanical-frequency curves for double-frequency turbogenerator

I_1=1, I_2=I_4=0.821, K_3=1.09×10⁴

Figures 7 and 8 show that except at very low values of the mechanical-system frequency the system response to the other rotor-air-gap-torque components (T_r) will be so low that the net effect cannot be as severe as the case of a line-to-line fault with no external resistance, since the (ΔT_L) term has only a small effect on the net shaft torques. At the lower range of mechanical-system frequencies the difference between the torques produced under these two conditions will be small. In general the most severe case is a line-to-line short circuit from full-load unity power factor with no external resistance.

Time to Crest Shaft Torque

The time required for the shaft torque to reach its crest is of some importance if greater than the minimum circuit-breaker interrupting time. Under this condition full crest torque might not be reached. As would be expected for systems of this nature, the time to crest torque is relatively short at low system frequencies and increases as resonance with an excitation frequency is approached. This effect is shown by the shaft-torque oscillograms of Figures 2 and 3A, which also show the decrease of time to crest as the decrement of the rotor air-gap torque is increased. Curves of time to crest torque are given in Figure 9, which further illustrate these effects. If there were no damping in the mechanical system, the maximum time to crest would be infinite, assuming infinite duration for the fault. However, as shown by Figure 9, the maximum time to crest is about eight cycles of 60-cycle frequency if the mechanical system has 60-cycle resonance. For natural frequencies below 50 cycles, the time to crest is below three cycles of 60-cycle frequency so that the full crest torque in general should be used for all considerations.

Synchronizing Out of Phase

In Figure 2 of reference 3 is presented an analysis of the crest synchronizing torque as a function of system reactance and angle of synchronization. For a given value of system reactance, the crest-synchronizing-torque increase is roughly proportional to angle of synchronization, being about 12 per unit at an angle of 90 degrees for a system reactance (X_s=X_d''). It increases with decreasing X_s. For a synchronizing angle of 30 degrees, it is also about 12 per unit when X_s=0. Shaft torques for synchronization 90 degrees out of phase with X_s=X_d'' are shown in Figures 7 and 8. This provides a fair basis for the more severe synchronizing torques that normally might be expected. The resulting shaft torques are as

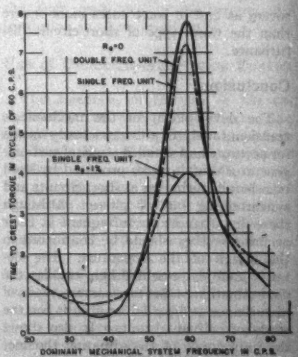


Figure 9. Curves showing time to crest shaft torque as a function of turbogenerator mechanical-system frequency

Use of Dielectric-Absorption Tests in Drying Out Large Generators

H. C. MARCROFT
ASSOCIATE AIEE

DIELECTRIC absorption is the name commonly given to the effect which takes place in electrical insulation when it is subjected to a direct potential, with reference particularly to the manner in which the resulting charging current into the insulation decreases with time. The time rate of change and the magnitude of the observed current are indications of the amount of absorbed moisture (among other things) existing in the insulation of large generators, which apparatus affords a practical application of the dielectric absorption phenomenon. A newly wound generator or a generator long idle contains moisture in the insulation which should be removed before full operating voltage is applied to the winding insulation.[1] The method of using the dielectric absorption effect to determine the state of dryness of large generators is presented as a new means of measurement and one better adapted to giving more information than methods previously used.

Dielectric Absorption

When a direct potential is suddenly applied to a generator armature winding, the current flowing into the winding will have three components:[2]

1. A capacitance current, resulting from the capacitance of the winding to the generator core.
2. Dielectric-absorption current, continuing much longer in time than the capacitance current and having a characteristic diminishing value.
3. Leakage current, the final constant value reached at infinite time.

It is the dielectric-absorption current (2) which gives the information which is useful in diagnosing insulation, because the shape of the dielectric-absorption current–time curve is influenced by the following factors:

1. Moisture in or over the insulation.
2. Nature or type of insulation.
3. Machine rating, voltage, and speed.
4. Temperature of the insulation.
5. Cleanliness of the insulation.
6. Previous charges in the dielectric.
7. Test-voltage value.

Of these factors, all but moisture are known or can be controlled, so that the dielectric-absorption curve may be used to indicate the relative amount of moisture in the dielectric.

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H. C. MARCROFT is a test engineer, Pennsylvania Water and Power Company, Baltimore, Md.

In testing a machine, the direct test voltage is applied to the winding suddenly and at a constant voltage. The elapsed time is recorded as the current readings are being taken. It has been found by experience that readings taken at 15-second intervals for the first minute, half-minute intervals for the second minute, and minute intervals for the remaining time up to ten minutes give the necessary data for a charge curve. If, at the end of ten minutes, the generator is suddenly connected to ground through the current instrument, a discharge current will flow, lesser in magnitude than the charge curve by the amount of the steady-leakage current; or in other words, the difference in the charge and discharge currents represents the leakage current, which is equal to the charge current at infinite time. In practice, the current and voltage readings are expressed in megohms.

It is necessary to have a steady supply of direct current in order to run a dielectric-absorption curve because the relatively large capacitance of the generator winding is able to store a sufficient electrical charge so that the normal commercial voltage fluctuations will result in the test current surging and even reversing. Some method must, therefore, be used to smooth the supply voltage. The curves which are discussed here were obtained by using a special testing set employing small dry cells as the voltage supply. The resulting curves are consequently very smooth.

The data taken on a test made on a nominally dry 10,000-kva turbogenerator are shown in Figure 1. The effect of dielectric absorption is shown in the decline of the charging current. Even at ten minutes time, the current is seen to be diminishing at a noticeable rate. It is this effect which has been neglected so often in previous practice in which short-time tests are made, frequently lasting less than 30 seconds. Such short-time tests result in values which are unreliable, since the tests are discontinued at a time when the resistance indication is changing with time at a fast rate. This effect is not sufficiently noticeable at the time of test because the scales of instruments usually used become crowded at increasing resistance values. In the case of instruments with manually generated power, the personal element of tiring of the operator frequently dictates the shorter test.

The first absorption test made on the generator of Figure 1 was at a potential of 500 volts, shown in curve 1. The discharge of this absorbed charge is indicated by curve 2. This sequence of tests was followed immediately by a charge test at 1,000 volts (curve 3), and the discharge of this charge (curve 4), which followed immediately.

The difference between the charge and discharge curves is shown by the dotted

Table I. Drying Generator Winding Showing Increase in Slope Factor

Generator *A*—13.3 Kv, 31,000 Kva, Three Phase, 60 Cycle

Test No.	Temp, C	Slope Factor	Drying Time, Hrs
1	26	0.22	0
2	58	0.30	15
3	76	0.41	27
4	75	0.62	39
5	75	0.72	51
6	75	0.99	63
7	75	1.12	75
8	75	1.44	87
9	35.7	1.88	87

line in both cases and is approximately the final leakage current for the 500-volt test. For the 1,000-volt test, the dotted curve is not a true leakage value because the charge curve 3 has a lower value, and the discharge curve 4 has a higher value than would be the case if the test had been made on a winding not having an absorbed charge still remaining in the dielectric. Error in insulation-resistance measurements is introduced when the measurements are made on a generator insulation which is not completely discharged. On a large generator, the discharge time has been found to be an hour or more to drain a 500-volt charge of ten-minutes duration. The discharge time is not proportional to the charge voltage but increases faster than the voltage, within limits observed in these recorded tests.

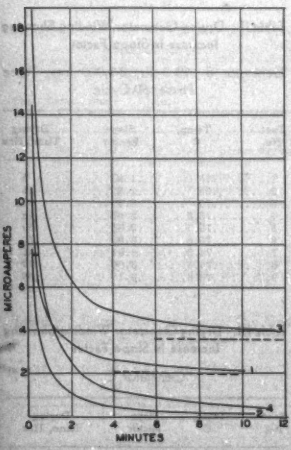

Figure 1. Charge and discharge curves at 500 and 1,000 volts on a 10,000-kva 1,800-rpm 13.3-kv 60-cycle three-phase generator

1. Charge at 500 volts
2. Discharge of run 1
3. Charge at 1,000 volts
4. Discharge of run 3

Both positive and negative charges can exist at the same time in a generator insulation. One interesting example of this effect was demonstrated on a dielectric-absorption test in which a charge of positive polarity was followed immediately by a shorter charge of negative polarity. When the generator was grounded and the discharge current was being observed, the negative charge was found to leave the generator first followed by the positive charge. The meter indicated a definite and rather abrupt reversal of current during the discharge.

Moisture Effects

The amount of absorbed moisture in the generator insulation will affect the number of leakage paths containing free ions; the resistance is lower for the greater number of such paths. When this moisture is driven out of the insulation, as it is on a dry-out run, the number of leakage paths is greatly reduced and the leakage resistance becomes greater. At the same time, the effect of the ions being held bound on the boundaries of the surfaces separating dissimilar insulating substances is made apparent. The effect may be likened to the charging of many small capacitors joined together by countless ties of very high resistance. The charges which these capacitors take are recoverable by grounding the generator winding, in which case they will flow in the opposite direction to that of the charge. Interfacial polarization[4] is the term often used to describe the condition of the insulation containing charges resulting from applied voltage across the insulation.

The degree of dryness of the insulation is reflected in the shape of the dielectric-absorption charging-current curve taken over a period of time.

Effect of Test Voltage

Moisture in insulation decreases its resistance on d-c measurements. The apparent resistance of hygroscopic insulation containing water decreases with an increase in the test voltage used. This was noticeable to a certain extent on dielectric-absorption tests made on a number of large generators. The mechanism by which this change in resistance occurs is explained by a theory, confirmed by experiments, given by S. Evershed[3] in 1913. He calls this effect "endosmosis." According to this theory, the water in insulation which causes leakage paths is a very minute fraction of the water in the insulation. Under increasing voltage stress, the so-called dormant water is forced out of the cross channels and into the direct resistance paths, enlarging the conducting water films and thus lowering the resistance. The practical difficulty in using this effect on tests is the requirement of a large voltage range of d-c supply having a very steady voltage and being sufficiently portable. The testing time and especially the time consumed in discharging the insulation is often prohibitive.

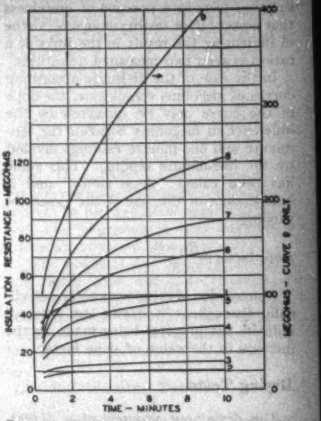

Figure 2. Insulation-resistance–time curves for generator *A*—31,000 kva, 13.3 kv, 60 cycle, 109 rpm

1. Cold, before dryout
2. Drying run started, 15 hours, 58 degrees centigrade
3. Drying continued, 27 hours, 76 degrees centigrade
4. Drying continued, 39 hours, 75 degrees centigrade
5. Drying continued, 51 hours, 75 degrees centigrade
6. Drying continued, 63 hours, 75 degrees centigrade
7. Drying continued, 75 hours, 75 degrees centigrade
8. Drying ended, 87 hours, 75 degrees centigrade
9. Cold, after dryout, 35.7 degrees centigrade

Use of Dielectric-Absorption Curves

The steepness of the rise of the resistance curve with time indicates the relative amount of moisture present in the insulation. However, all generator insulations do not have the same curves. For example, some generators are wound with coils having the end turns treated with a conducting paint to control the corona which otherwise might exist in the end-turn spaces. Such a machine has a lower and flatter absorption curve than a generator without end-turn corona control treatment. The larger and slower-speed generators have more coils and lower resistance than smaller high-speed machines yet the shapes of the absorption curves would be the same, all other things being unchanged. This is a fortunate circumstance as it puts the dielectric-ab-

sorption tests in a position of usefulness that power factor testing enjoys by virtue of indicating the result in the form of a ratio between two measured quantities.

In the case of the dielectric-absorption curves of megohms versus time, the slope of the curve may be indicated by the difference in megohms between the ten-minute and one-minute readings divided by the one-minute reading. This value has been called "slope factor" and is independent of the size of the generator winding.

$$\text{Slope factor} = \frac{R_{10} - R_1}{R_1}$$

A succession of these tests made periodically throughout a drying-out run will indicate the progress being made by the increase in the value of slope factor.

Drying Tests

The drying-out progress of a 31,000-kva three-phase 60-cycle hydro generator (generator *A*) is shown in Figure 2. This machine has mica-tape insulation throughout the entire coil, the coil-end connections, and pole leads or group leads. The tie cords on the coils are linen but on the end connections and phase-collector busses they are fiber glass. This generator was out of service two months during which time moisture was absorbed. There is no resistance varnish used on these coils. The curves show the resistance of the insulation for 500 volts impressed and for a charging time of ten minutes. The corresponding values of temperature of the insulation and slope factor, as the drying run progressed, are given in Table I. The slope factor increased from 0.22 at the start to 1.44 at the end of drying run which was of 87 hours' duration. A value of 1.25 slope factor has been arbitrarily set as a satisfactory dry value for this class of generator at 75 degrees centigrade approximately. The increase in slope factor to 1.88 after the generator had cooled is caused principally by the fact that the resistance-temperature curves for one-minute and ten-minute values do not have the same slope.

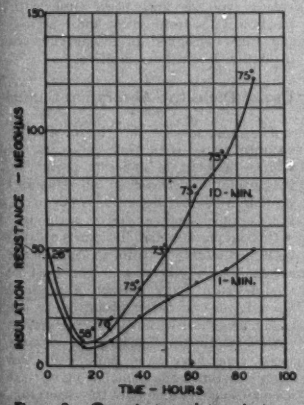

Figure 3. One-minute and ten-minute resistance values during drying run on generator *A*

The two curves of Figure 3 show the one-minute and ten-minute resistance values obtained from Figure 2 during the dryout time of 87 hours. The divergence of the two curves indicates graphically the increasing drying of the insulation. Obviously, the slope factor will continue to rise beyond the end of the curve with further drying. A generator of this type in steady service will have a value of slope factor in the order of two or three at 60 degrees centigrade.

Sufficient outage time was not available to allow the continuation of the dry-out curves to a steady state at this time. However, the drying was continued beyond the time at which the ohmmeter method indicated the machine to be dry, that is, when two successive insulation readings are constant with a drying period between readings. This was also true of other generators which were tested.

In Tables II and III are shown the results obtained in drying two additional generators of the same characteristics and rating as generator *A* of Table I. The course of drying of a 37,500-kva 25-cycle single-phase 13.3-kv hydro generator is shown in Table IV, in which the drying run was of 97 hours' duration. This was the initial dry-out following the erection of the machine. Similar curves are obtained on these machines as for generator *A*, Figures 2 and 3. For reasons discussed in the following heading, constant temperature should be maintained during a dry-out run.

Temperature Effects

There is a marked temperature effect on generator-insulation resistance as may be seen from Figures 4 and 5. Tests were made at 500 volts in 1938 and in 1940 on a number of large 13.3-kv hydro generators for the purpose of comparing the resistance-temperature curves over a period of time.

In order to minimize the effect of humidity, all tests were made only after the generators had been carrying a good load for at least two weeks prior to the tests. The first test point was always at the highest temperature and, as the generator cooled, the points at lower temperature were obtained. This procedure usually required 24 hours for a test.

Temperature of the insulation was obtained from the embedded resistance detectors; the average of the six was used for the nominal temperature. It is desirable to raise the generator temperature considerably above the tempera-

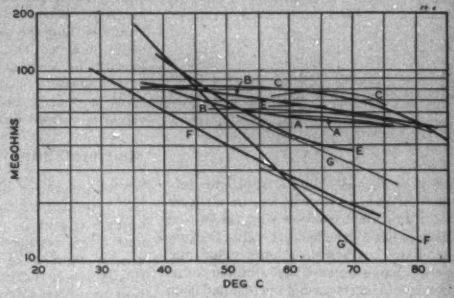

Figure 4. One-minute resistance-temperature curves for six large water-wheel generators showing changes in resistance between 1938 and 1940

Light lines, 1938 tests

Heavy lines, 1940 tests

Table II. Drying Generator Winding Showing Increase in Slope Factor

Generator *B*—13.3 Kv, 31,000 Kva, Three Phase, 60 Cycle

Test No.	Temp, C	Slope Factor	Drying Time, Hrs
1	15	1.83	0
2	69	1.83	24
3	75	2.32	36
4	73.2	2.63	48
5	73.5	2.85	60
6	75.5	2.80	72
7	74.2	2.91	84
8	74.4	3.06	96
9	73.8	3.1	108

Table III. Drying Generator Winding Showing Increase in Slope Factor

Generator *C*

Test No.	Temp, C	Slope Factor	Drying Time, Hrs
1	26	0.17	0
2	38	0.33	22
3	70	0.323	34
4	70	0.60	46
5	70.2	0.78	55
6	71.4	1.06	70
7	74.5	1.09	83
8	70	1.26	94
	74	2.77	In steady service

ture of the first test point in order to allow the temperature gradient of the insulation to become a minimum for the first test point.

Figure 4 gives the values obtained from the dielectric-absorption curves at one minute time; Figure 5 gives the values from the dielectric-absorption curves at ten minutes time.

The heavy curves are the tests made in 1940; the lighter curves are for the 1938 tests.

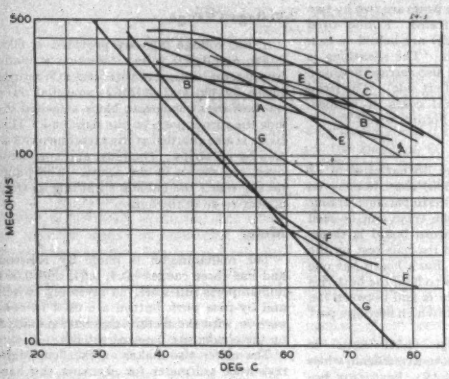

Figure 5. Ten-minute resistance–temperature curves for same conditions as in Figure 4

Table IV. Drying Generator Winding Showing Increase in Slope Factor

Generator *D*—13.3 Kv, 37,500 Kva, One Phase, 25 Cycle

Test No.	Temp, C	Slope Factor	Drying Time, Hrs	Winding Condition
1	30	0.27	0	Cold—before drying
2	49	0.30	16	Warming up
3	72	0.14	29	Warming up
4	72	0.43	41	Warming up
5	75	0.52	47	Up to final temp
6	75	0.62	53	
7	74	1.0	65	
8	75	1.25	77	
9	75	1.41	89	
10	75	1.5	97	Dryout run stopped
11	25	1.57		Cold—after drying

Table V. Slope-Factor Values for Dry Generators in Daily Operation

These Values Are Obtained From Figures 4 and 5, 1940 Tests

Generator	Manufacturer	Slope Factor 1940 75 C	1940 60 C	1938 60 C
A	*A*	1.55	2.3	2.8
B	*A*	1.86	2.2	2.8
C	*A*	1.78	2.0	3.7
E	*A*		3.1	2.7
F	*B*	0.69	0.65	0.71
G	*B*	0.44	0.65	1.30

The generator number is shown on each curve. Generators *A*, *B*, *C*, and *E* are made by one manufacturer; generators *G* and *F* are made by another manufacturer. There is a noticeable difference in the two machines in the slopes of the temperature curves. Both kinds of generators have mica insulation as the slot insulation. The difference in the shape and magnitude of the curves is caused by the different manner of insulating the coil sections by the two manufacturers.

Table V gives the slope factors of these machines at 60 degrees centigrade and 75 degrees centigrade for generators in daily operation under normal load.

These figures are therefore typical for nominally dry generators. The 1940 curves of Figures 4 and 5 were used for data in Table V. The slope factor generally increases with decreased temperature, caused by the ten-minute value of resistance increasing at a faster rate than the one-minute value.

From these results, it is evident that at a temperature of 60 degrees centigrade, slope factor values of over 2.0 may be regularly obtained from generators with mica-tape insulation and no end-section corona treatment. Generators *F* and *G* have the end sections protected with varnished cambric, which apparently has lower resistance than the other generators, and which is reflected in the slope factor figures. This class of winding would appear to be dry with a slope factor value of 0.50 or more. Thus it becomes desirable to know the type of the coil insulation in applying the method of dielectric-absorption curves to the dryout tests, in cases where the slope factor is of the lower order.

The temperature–resistance curves (Figure 5) show that generators of different manufacture (and consequently a certain difference in insulation) have temperature curves which may differ in slope. There is even in some cases a change of slope in these curves for the same machine from year to year. Generators *A*, *B*, *C*, *F*, *G* are three-phase, 31,111-kva machines; generator *E* is a one-phase, 35,000-kva machine. All of these generators have closed ventilation. Generator *G* has had some trouble with oil film on the winding, which may explain the lowered resistance for the 1940 test. Not enough is yet known of the yearly changes of resistance–temperature curves to say definitely what the reason is. The indication is that humidity is probably responsible in most cases.

The slopes of the temperature curves of Figure 5 lie anywhere between the extremes of eight degrees to 33.5 degrees centigrade to double the resistance. The former applies to generator *G* and the latter to generator *B*.

Divided-Winding Tests

The foregoing tests were all made with the whole winding connected together and energized between winding and ground. On generators *A* and *C*, dielectric-absorption curves were made later with the winding separated into the three phases, so that by energizing one phase at a time, with the other two grounded, an indication of interphase-insulation resistance was obtained. These values are given in Table VI.

The values of slope factor for tests between phase windings are not necessarily the same as for the entire winding to core. The leakage paths are very different and depend not only upon the coil-insulation material but also upon additional materials such as cording of various types and supporting blocks. Also, the kind of varnish used on the end-coil sections becomes very important whereas this has much less effect on the measurement of resistance between the total winding and the core. For the purpose of determining the dryness of a generator, the dielectric-absorption curve of the total winding to the core is the one best adapted to the purpose. Where a generator winding is suspected of being damaged, a test between phases may be employed to determine whether or not all phases have deteriorated equally. A

Table VI. Slope-Factor Values for Tests Between Phase Windings

Generator	Phase	Megohms One Minute	Megohms Ten Minutes	Slope Factor	Temp, C
A	*A*	69.5	114	0.64	81.2
	B	78.0	125	0.60	80.6
	C	70.2	109	0.56	79.8
	All	50.6	141	1.8	83.8
C	*A*	104	192	0.84	77.6
	B	100	177	0.77	79
	C	113	208	0.84	76
	All	81	306	2.3	74

high-voltage d-c absorption test should prove of more value in such a case than the low-voltage test because of the possibility of finding concentrated faults more readily by high leakage current.[4]

Conclusion

The use of dielectric-absorption curves in drying out large generators is an improvement over previous practices. More information is obtained by these curves than can be gained from spot readings which are taken at short charging times. The record of the dry-out run has been put on an exact basis. The condition of a generator with respect to moisture can be expressed in terms of slope factor. Dielectric-absorption curves taken periodically during a drying run will give the data necessary to observe the progress of the moisture removal as indicated by the rise in slope factor. It is desirable that constant temperature be maintained throughout the run.

The value of the slope factor will vary over a considerable range depending upon the type of insulation and its treatment.

The accumulation of temperature–resistance curves, at ten-minute time, over a period of years, should provide a good indication of changes in or over the insulation of the generator winding.

Figure 6. Generator-insulation-test table

Appendix. Description of Insulation-Test Table

General Construction

The table is constructed of fir wood and measures 19 by 40 inches by 32 inches high, including wheels. The posts are two by two inches, bolted to the frame. Rubber-tired truck casters (four-inch) are bolted to iron plates across the ends. The sheathing is 1/4-inch bakelite which also carries the guard and ground terminals (left side). The wood is finished with several coats of varnish. The table is shown in Figures 6 and 7.

Batteries

The support for the 35 batteries of 45 volts each (Burgess 5308) consists of seven trays of white pine boiled in paraffin for four hours. The ends of the trays can be seen in Figure 6. The bottom board is three-quarter-inch stock and its ends rest on the table cross members. Each board has one side and two end pieces to hold the batteries in place. A strip of tin is laid between the trays and the cross-rails which becomes part of the guard circuit.

The battery voltage (1,500 volts) is broken up into sections to avoid drain when not in use and for safety. Each tray becomes a group (235 volts) separated by six switches. The switch mounting board is boiled in paraffin and is guarded at the point of attachment to the corner posts by tin strips. At the left end of this board, a metal box is attached, which contains three batteries (Burgess 5540). Each three-volt tap is brought out to a point on a rotary switch on the top panel for voltage adjustment. Nine steps are available to take care of any voltage adjustment. The "5308" batteries have taps at 22.5 volts.

Charge–Discharge Switch

The main "charge–discharge" switch is built from a Trumbull 3821½ 500-volt 30-ampere switch. The slate base and fiber crosspiece on the blades were discarded, and the metal parts were mounted on three "condensite" blocks which were mounted on an iron V frame. This was done for several reasons:

1. The separation between blades carrying opposite potentials was increased.

2. Condensite is a much better insulator than slate and fiber.

3. The frame of one-fourth by one-inch strap iron could be bent so that the throw from charge to discharge position was short and easily done.

4. The iron framework made possible an ideal guard circuit between switch elements. The handle of the switch extends through the top condensite panel which is slotted for that purpose. Figure 6 shows this switch mounted under the left corner of the table.

Voltage Change

Three voltage taps are provided at 500, 1,000, and 1,500 volts. Selection is made by plugging into one of three jacks (Westinghouse 591496 and 591497), mounted on a one-half-inch condensite block attached inside the corner posts on the right end. This block is also guarded at the attachment location by tin strips. The plug, and two dummies, are shown in the figure. The plugs do not touch the outside sheathing as they appear to do in the figure.

Meter

The milliammeter is made by Rawson and has three ranges—0.4, 0.04, and 0.004 milliamperes full scale. A reversing switch and by-pass push button are used in connection with the meter; these are mounted on the condensite panel at the left.

The meter also makes an excellent high-resistance voltmeter for checking the batteries when used with a standard ten-megohm resistor. The batteries should not be checked with an ordinary voltmeter as such procedure depletes the battery faster than testing would do.

Wiring

The wiring is shown in Figure 7 and is done with benchboard wire. Wiring support blocks are of bakelite and guarded with tin strips under the blocks. A fuse block is provided in the negative battery lead to guard against internal trouble. Another fuse is located in the positive lead to guard against external faults. This fuse is rated 1,000 volts, one-sixteenth ampere, and is sufficient for tests at 500 volts; tests at higher voltages generally require a larger rating for large generator testing. The protective resistor of 2,870 ohms limits a possible short-circuit current to a reasonable value.

The high-voltage cable lead is single-conductor number 4 "superservice" flexible rubber-covered and is 25 feet long.

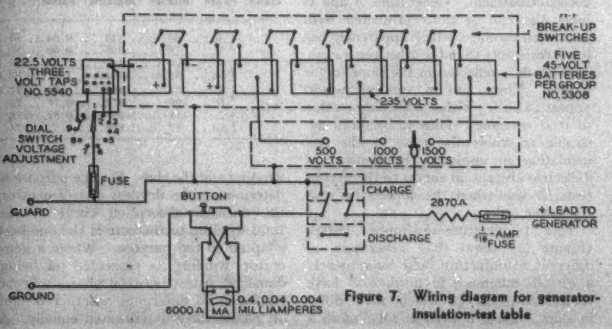

Figure 7. Wiring diagram for generator-insulation-test table

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Improving Stability by Rapid Closing of Bus-Tie Switches

EDWARD W. KIMBARK
MEMBER AIEE

RAPID opening of circuit breakers on faulted lines has been recognized for many years as one of the most effective ways of improving power-system stability. Rapid opening followed by rapid reclosing has been used more recently and gives further improvement in stability if the fault is transitory. Rapid closing of normally open breakers offers yet another means of improving stability—a means which has never been put into practice, so far as the author is aware, but which promises to have a field of usefulness.

This paper presents the results of calculations of the power limit of a particular two-machine power system, both with the proposed switching scheme and, for comparison, with various other switching schemes which are in common use.

Figure 1, which is reprinted from an AIEE committee report[1] published in 1937, shows the effect of the presence or absence of high-voltage bussing at the ends of a double-circuit line over which power is being transmitted from a hydroelectric station to a large receiving system when a two-wire-to-ground fault occurs near the sending end of one circuit and is cleared by simultaneous opening of the breakers at both ends of that circuit. Two curves of power limit versus fault duration are drawn in this figure: curve *A* for the transmission system without high-voltage busses, curve *B* for the system with high-voltage busses. High-voltage bussing is detrimental to stability as long as the fault is on the line because the fault then pulls down the voltage of both circuits instead of only one and thus impairs their capacity to transfer power. After clearing of the fault, however, the bussing is beneficial because it lowers the reactance between generators by connecting two banks of transformers in parallel at each end of the remaining transmission circuit. With slow clearing of the fault, the detrimental effect of bussing during the fault predominates over the beneficial effect after clearing the fault. With rapid clearing, the opposite is true. As a result, curve *B* is below curve *A* at long fault durations and is above curve *A* at short durations. The curves cross at a fault duration of about 0.15 second (nine cycles on the basis of 60 cycles per second), which is the time of clearing if standard eight-cycle circuit breakers and one-cycle relays are used.

The thought naturally occurs: Inasmuch as high-voltage bussing is detrimental during the fault but beneficial after the fault, why not use bus-tie switches which are normally open but which close simultaneously with the opening of the breakers which disconnect the faulted line? The same protective relays which open each line circuit breaker could be used to close the nearby bus-tie switch.

When such switching is used on the power system of Figure 1, the calculated power limit as a function of fault duration is as shown by curve *C* of Figure 2. Curves *A* and *B* are the same in Figure 2 as in Figure 1 except that they have been recalculated using voltages behind transient reactance at each end of 1.00 unit instead of some higher value.

If the fault is cleared instantly, the power limit does not depend on whether the bus-tie switches are open or closed before and during the fault, but it does depend on the position of these switches after clearing the fault. Therefore, curve *C* intersects curve *B* at zero fault duration because both curves represent switching schemes in which the bus-tie switches are closed after clearing of the fault. However, if the fault persists a long while, the power limit is determined chiefly by conditions during the fault and very little by conditions after clearing. Therefore, curve *C* approaches curve *A* as the fault duration increases since both curves represent switching schemes in which the bus-tie switches are open during the fault. At intermediate values of clearing time curve *C* is above both curves *A* and *B*, showing that the power limit has been raised by closing the bus-tie switches simultaneously with the opening of the line breakers. The increase in power limit over that obtainable with the better of the first two arrangements (bus ties always open or always closed) is greatest for clearing times in the neighborhood of those afforded by modern high-speed relays and breakers. With 0.15-second (nine-cycle) clearing the power limit is increased from 0.87 to 0.98 per unit—an increase of 12 or 13 per cent over the first-named value. With 0.10-second (six-cycle) clearing the power limit is increased from 0.98 to 1.05 per unit—an increase of seven per cent. The improvement attainable in this case through rapid closing of bus-tie switches in conjunction with eight-cycle breakers is just equal to the improvement attainable through replacing eight-cycle breakers with five-cycle breakers.

The transient power limits calculated for 0.10-second, 0.15-second, and 0.20-second clearing of a two-wire-to-ground fault are listed in Table I for the three kinds of switching which have been considered already (*A*, *B*, *C*) and for other kinds of switching (*D* to *N*) which are to be considered subsequently. The steady-state power limit for the final circuit condition is also tabulated for each kind of switching.

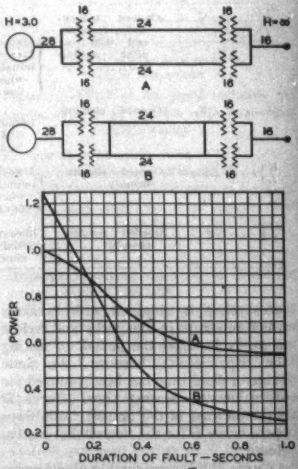

Figure 1. Effect of bussing arrangement on stability limits; double line-to-ground fault at sending end (reprinted from reference 1)

A—Low-voltage bussing
B—High-voltage bussing
System reactance shown in per cent; inertia constant *H* = kilowatt-seconds per kilovolt-ampere

Rapid Reclosing

It is interesting to compare the improvement in stability obtainable through the use of rapidly closed ties with that obtainable through rapid reclosing of the line breakers. Curves *D* and *E*, Figure 3, show calculated power limit versus fault duration if the breakers are closed 0.25 second (15 cycles) after interrupting fault current. This value of dead time

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EDWARD W. KIMBARK is an associate professor in the department of electrical engineering, Northwestern University, Evanston, Ill. This paper was written while he was visiting associate professor of electrical communications, Massachusetts Institute of Technology, Boston, Mass.

Table I. Comparison of Power Limits for Various Kinds of Switching

Two-Wire-to-Ground Fault at Sending End of One Line of the Power System of Figure 1

Curve	No. of High-Voltage Switching Stations	Kind of Switching: Line Breakers	Kind of Switching: Tie Switches	Transient Power Limit in Per Unit if Clearing Time of First Breaker Is: 0.10 Sec	0.15 Sec	0.20 Sec	Steady-State Power Limit of Final Condition (Per Unit)
A	2	Opened simultaneously	Always open	0.88	0.84	0.79	0.93
B			Always closed	0.98	0.87	0.76	1.09
C			Initially open; close when line breakers open	1.05	0.98	0.91	1.09
D	2	Opened simultaneously and reclosed 0.25 sec later	Always open	0.98	0.90	0.83	1.25
E			Always closed	1.00	0.83	0.77	1.25
F			Initially open; close when line breakers open	1.08	0.99	0.91	1.25
G	2	Opened sequentially, receiving end 0.30 sec after sending end	Always open	0.75	0.74	0.71	0.93
H			Always closed	0.75	0.70	0.63	1.09
I			Initially open; close when adjacent line breakers open	0.85	0.80	0.76	1.09
J	2	Opened simultaneously	Initially open; close 0.05 sec after line breakers open		0.94		1.09
K	3	Opened simultaneously	Always closed	1.04	0.91	0.78	1.17
L			Initially open; close when adjacent line breakers open	1.12	1.03	0.94	1.17
M	∞	Opened simultaneously	Always closed	1.10	0.95	0.83	1.25
N			Initially open, then closed	1.21	1.09	0.99	1.25

(15 cycles) is obtained with breakers which interrupt in five cycles and reclose in 20 cycles after the instant of closing the trip circuit; however, the same value of dead time has been assumed for all values of clearing time. Curve *D* is for the case of the tie switches always open, curve *E* for the tie switches always closed.

Curve *D* lies considerably above curve *A*, particularly at short fault durations, because of the effect of reclosure; at long fault durations, however, *D* approaches *A*. Curve *E* lies above curve *B* for the same reason, though the difference between *E* and *B* is less than the difference between *D* and *A*. However, neither *D* nor *E* lies much above *B* at the usual clearing times. At 0.10-second fault duration *D* coincides with *B*, and *E* is only 0.02 per unit above *B*. At 0.15-second fault duration *D* is only 0.03 above *B*, and *E* is only 0.02 above *B*. These results are in general agreement with conclusions previously reached by others,[2] to the effect that rapid reclosing is of little benefit after two-wire-to-ground or three-phase faults on a sectionalized double-circuit line, especially if the generators have low inertia for the amount of power transmitted (as is true of hydroelectric generators with little local load).

Curve *D* is below curve *C* at all values of fault duration and *E* is below *C* except for fault durations less than four cycles. Accordingly, rapid reclosing of the line breakers is less effective than rapid closing of the bus-tie switches unless the fault can be cleared with extreme rapidity (requiring three-cycle or faster breakers).

The assumption of a shorter dead time than 0.25 second (15 cycles) would raise curves *D* and *E*, especially at short fault durations. If the dead time is decreased too much, however, the fault arc is likely to restrike when the line breakers reclose. The dead time should be about 10 or 12 cycles at 138 kv and longer at higher voltages. Therefore the possibility of raising the power limit by faster reclosing has decided limits. Zero dead time (if such were possible) would raise curve *E* at zero fault duration to the transient power limit 1.39, which considerably exceeds the steady-state power limit of 1.25, but curve *E* would still approach curve *B* rapidly as the fault duration increased. The steep slope at short fault durations of curves such as *E* for rapid reclosing as compared with the slope of curves such as *B* for no reclosing, has been pointed out previously.[2]

The use of rapid closing of bus-tie switches followed by reclosing of the line breakers 0.25 second later gives a slightly higher power limit than does the closing of bus ties alone. This is shown by curve *F*, Figure 3, which lies above curve *C*, especially at short fault durations. The improvement due to reclosing is slight at fault durations of 0.10 and 0.15 second.

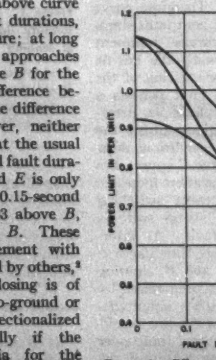

Figure 2. Effect of the rapid closing of bus-tie switches on stability of the power system of Figure 1

A—Bus-tie switches always open
B—Bus-tie switches always closed
C—Bus-tie switches initially open but close simultaneously with opening of line breakers

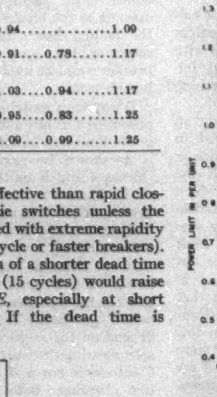

Figure 3. Effect of the rapid reclosing of the line breakers on stability

A, *B*, *C*—Same as in Figure 2: no reclosing
D, *E*, *F*—With reclosing after 0.25-second dead time
D—Bus-tie switches always open
E—Bus-tie switches always closed
F—Bus-tie switches initially open but close simultaneously with opening of line breakers

Intermediate Switching Stations

A common method of improving the stability of a power system like that shown in Figure 1 is to add one or more high-voltage switching stations at intermediate points of the line. The effect

of one intermediate switching station at the center of the transmission line, in addition to the two high-voltage terminal switching stations, is shown in Figure 4. Curves *B* and *C*, as in previous figures, are for terminal bussing only. Curves *K* and *L* are for an additional switching station at the center. Curves *B* and *K* are for permanent bussing at all three switching stations; while *C* and *L* are for rapidly closed bus-tie switches at all stations. If solid bussing at the terminals (curve *B*) be taken as the original condition, the improvement due to the addition of rapid closing of bus-tie switches at the two terminals (curve *C*) is greater than the improvement due to the intermediate switching station (curve *K*) at clearing times of 0.10 second (six

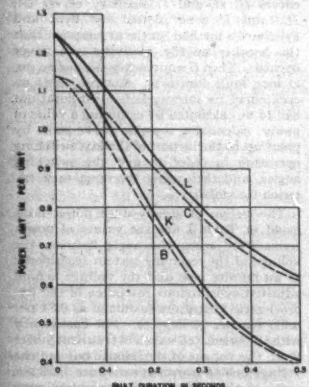

Figure 4. Effect of one intermediate high-voltage switching station on stability

B, *C*—Same as in Figure 2, high-voltage bussing at terminals only

K, *L*—One intermediate switching station added

B, *K*—Bus-tie switches at all stations always closed

C, *L*—Bus-tie switches at all stations initially open but close simultaneously with opening of line breakers

cycles) or more. The addition of two circuit-closing switches at the ends of the lines is more effective than addition of four circuit breakers at the middle of the line.

Even if the intermediate switching station is used (curve *K*), a considerable additional improvement is effected by the addition of three rapidly closed bus-tie switches (curve *L*). Again the use of rapidly closed bus-tie switches in conjunction with eight-cycle line breakers gives as much increase of power limit as does the replacement of eight-cycle breakers by five-cycle breakers.

The greatest possible improvement due to the addition of intermediate switching stations would occur if a very great number of such stations was used, spaced very closely together. (If faults occurred nowhere but at the sending end, one additional station very near the sending end would have the same effect.) Curves for this condition are not given, but values of power limit are entered in Table I, lines *M* and *N*. These values show that an infinite number of intermediate switching stations (line *M*) are more effective than rapidly closed bus-tie switches at the terminals only (line *C*) for a clearing time of 0.10 second but are less effective at 0.15 second and longer clearing times, and even if a large number of switching stations are used, the provision of rapidly closed bus-tie switches at all stations (line *N*) raises the power limit further. Once again the use of the bus-tie switches with eight-cycle breakers is as effective as replacing eight-cycle breakers with five-cycle breakers.

Sequential Switching

Rapid reclosing is of negligible aid to stability unless the breakers at both ends of the faulted line are opened rapidly and almost simultaneously. If a relaying scheme is used which requires time delay in the opening of the breaker at one end of the line in case of a fault near the other end, neither breaker can be reclosed successfully until the required dead time has elapsed after the opening of the second breaker. It is then too late to do much good.

Closing of bus ties, on the other hand, is of some benefit in conjunction with sequential fault clearing. When the line breaker at the end near the fault opens, the adjacent bus tie simultaneously closes, paralleling the two banks of transformers. The bus tie at the other end is still open, so the fault is connected to the sound part of the system through high reactance. Later, when the second line breaker opens, the second bus tie simultaneously closes, paralleling the transformers at that end.

Curves *G*, *H*, and *I*, Figure 5, show the calculated power limit of the system of Figure 1 for a two-wire-to-ground fault at the sending end cleared sequentially. Power limit is plotted as a function of the time required to open the breaker at the sending end (including relay time). The breaker at the receiving end is assumed to open 0.30 second (18 cycles) after the breaker at the sending end. Curve *G*, for bus ties always open, and curve *H*, for bus ties always closed, cross at 0.10 second. Curve *I*, for bus ties closed simultaneously with opening of the adjacent line breakers, lies above both *G* and *H*. The power limit is raised from 0.78 to 0.85 per unit with 0.10-second clearing at the sending end, and from 0.74 to 0.80 per unit with 0.15-second clearing. These increases are nine and eight per cent, respectively. The improvement attainable through synchronized closing of bus-tie switches in conjunction with eight-cycle breakers is slightly greater than that attainable

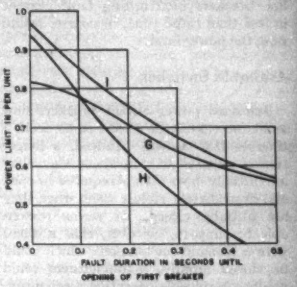

Figure 5. Effect of the rapid reclosing of bus-tie switches on stability with sequential fault clearing

G—Bus-tie switches always open

H—Bus-tie switches always closed

I—Bus-tie switches initially open, each closed simultaneously with opening of adjacent line breaker

through replacing eight-cycle breakers with five-cycle breakers.

However, much greater improvement can be effected through the addition of pilot relaying to obtain simultaneous high-speed opening of the breakers at both ends than can be obtained through the addition of synchronized bus-tie switches. Curve *B* is 26 per cent higher than either curve *G* or *H* at 0.10 second and 18 per cent higher at 0.15 second. Nevertheless, it is of interest to know that some benefit would be obtained in the event of a fault by leaving synchronized bus-tie switches in service during the outage of a pilot channel.

Imperfect Synchronization

It is obvious that, for the greatest effectiveness, each bus-tie switch should close simultaneously with the opening of the associated line circuit breaker. Even though not perfectly timed, however, these switches can still improve stability. In order to obtain an idea of the effect of imperfect synchronization, the power limit was calculated for the case in which the fault was cleared in 0.15 second and both bus-tie switches were closed 0.05 second later. The power limit was found to be 0.94 per unit as compared with 0.98 for perfect synchronization. Thus an increase of 37.5 per cent in the closing time of the switch (from 8 to 11 cycles) gives four per cent decrease in power limit. The decrease is the same as that caused by delaying the opening of the line breakers half as long, or 0.025

second, with simultaneous closing of the tie switches (curve *C*). Early closing of the tie switches would probably decrease the power limit more than late closing, but would be less likely to occur. Any lack of synchronization due to the line breakers interrupting fault current in less than rated time, of course, would raise the power limit.

Available Switches

Standard power circuit breakers now available cannot be closed in as short a time as 0.15 second. Indeed, a longer time is required to close them when they are initially open than is required to open and immediately reclose them when they are initially closed. It seems reasonable to suppose, however, that if there were a demand for breakers which could be closed rapidly, manufacturers could produce a suitable operating mechanism.

Rapid-closing bus-tie switches could be so operated that they would never be required to interrupt short-circuit current or, perhaps, even load current. For such service an air-break switch might be suitable.

Conclusions

The following conclusions may be drawn from this study regarding the suitability of rapid closing of bus-tie switches for raising the power limit of the power transmission system of Figure 1 (based on the clearing of a two-wire-to-ground fault at the sending end of one circuit):

1. With 0.15-second (nine-cycle) fault clearing, the power limit is increased 12 per cent by rapid closing of the bus-tie switches; with 0.10-second (six-cycle) clearing, seven per cent.

2. The increase in power limit due to the addition of rapid-closing bus-tie switches to 0.15-second fault clearing is the same as the increase produced by speeding up the fault clearing from 0.15 to 0.10 second (changing eight-cycle breakers to five-cycle breakers).

3. The increase in power limit due to rapid closing of bus-tie switches is greater than the increase attainable through rapid reclosing of the line breakers with 0.25-second dead time for all fault-clearing times except those under 0.07 second (four cycles), and with 0.10-second or 0.15-second fault clearing, the increase is three or four times as great.

4. Rapid closing of bus-tie switches is effective even with permanent faults, whereas rapid reclosing is beneficial only with transitory faults and is detrimental with permanent faults. Therefore, rapid closing of bus-tie switches is applicable to underground cable systems.

5. Rapid reclosing is effective with double-circuit transitory faults, whereas closing of bus ties is not. However, the power limit with double-circuit faults is much lower than that with single-circuit faults.

6. The increase in power limit due to rapid closing of bus-tie switches at the line terminals is greater than the increase attainable through the addition of an intermediate high-voltage switching station at the middle of the line for all fault-clearing times except those under 0.08 second (five cycles).

7. Even if rapid reclosing or additional switching stations are used to increase the power limit, considerable further increase can be obtained through use of rapidly closed bus-tie switches.

8. Rapid closing of bus-tie switches can be employed in conjunction with sequential clearing of faults and when so employed it raises the power limit eight or nine per cent whereas reclosing is applicable only with simultaneous clearing. However, changing from sequential to simultaneous clearing gives two or three times as much improvement as the addition of rapid-closing bus-tie switches.

9. For best results, each bus-tie switch should close simultaneously with the opening of an adjacent line circuit breaker. Exact synchronization is not necessary, however.

Although the calculated results have been limited to the rapid closing of bus-tie switches on a double-circuit line, the principle proposed in this paper is not so limited. Stability will be improved by the closing of any switch simultaneously with the clearing of a fault, provided the transfer reactance between synchronous machines during the fault is lower with the switch open than with it closed and after clearing of the fault is lower with the switch closed than with it open.

Appendix. Methods of Calculation

In the power system of Figure 1, resistance and capacitance were neglected. Negative-sequence inductive reactances were assumed equal to the corresponding positive-sequence reactances given in the figure. Zero-sequence inductive reactances of the transmission lines were assumed to be twice as great as the positive-sequence values. The internal voltage of each generator (voltage behind transient reactance) was assumed always to be 1.00 per unit.

Curves of transient-power limit versus fault duration for kinds of switching which involved only one instant of switching after the inception of the fault (curves *A*, *B*, *C*, *K*, *L*, *M*, and *N*) were calculated by the rapid method of Byrd and Pritchard.[3] For kinds of switching which involved two instants of switching (curves *D* to *J* inclusive), a more laborious method had to be used, as follows: The point for zero fault duration was read from an auxiliary curve calculated by Byrd and Pritchard's method; the abscissa of the auxiliary curve was the time of the second switching operation (reclosing of line breakers for curves *D*, *E*, and *F*, opening of second line breaker for curves *G*, *H*, and *I*). For long fault durations the curve was known to approach closely some previously calculated curve; for example, curve *D* approaches curve *A*. In case of curves *G*, *H*, and *I*, auxiliary curves *G'*, *H'*, and *I'* were plotted by Byrd and Pritchard's method on the assumption that the breaker at the receiving end never opened. Then *G* approaches *G'*, and so on, at long fault durations. Several points on each curve for intermediate fault durations had to be calculated by assuming a value of power, calculating a swing curve point by point up to the instant of the last switching operation in order to find the switching angles, and then using the equal-area criterion for stability.

The values of steady-state power limit listed in Table I are the values of power transmitted when the angle between the voltage of the receiving system (considered as an infinite bus) and the voltage behind adjusted synchronous reactance of the hydroelectric generators (assumed as 0.84 per unit) reaches 90 degrees. For consistency with the calculated values of transient power limit, the voltage of the infinite bus and the voltage behind transient reactance (0.28 per unit) of the hydroelectric generators were both taken as 1.00 per unit. In every case the steady-state power limit thus computed for the final condition of the circuit exceeds the transient power limit for fault-clearing time of 0.10 second or longer.

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Transient Electrical Torques of Turbine Generators During Short Circuits and Synchronizing

H. S. KIRSCHBAUM
ASSOCIATE AIEE

THE calculation of shaft and frame stresses in turbine generators during short circuits or synchronizing is dependent upon a knowledge of the electrical torque developed at the rotor air gap. This torque generally contains unidirectional, fundamental-frequency, and second-harmonic components, all of which are damped. It is the steady components of torque which are of interest in the calculation of system stability, while all the components are of interest to the turbine generator designer.

The torques have been calculated on the assumption of an "ideal" synchronous machine[1] and the equations will not be applicable to all types of synchronous machines. The turbine generator and salient-pole machines with connected dampers are close approximations during subtransient and transient periods. The salient-pole machine with unconnected dampers or no dampers at all is furthest removed in its characteristics from the ideal machine and will have torques containing all odd and even harmonics.[2] The unidirectional torque would be extremely difficult to calculate for such machines.

Various authors have presented torque equations derived by different approaches.[2,3,4,11] Nickle, Pierce, and Henderson thoroughly treated the alternating torques during single-phase short circuits by a combination of the constant-flux-linkages theorem and Park's torque equation.[5] They did not consider loss torques. Stone and Kilgore, in calculating the unidirectional torques during short circuit, assumed that all ohmic losses in the machine would appear as torque. This resulted in much too high a value of unidirectional torque. Whitney and Criner presented equations for single-phase, three-phase, and double-line-to-ground faults; these equations contained both the unidirectional and alternating components of torque. However, several terms of the equation for the double-line-to-ground fault were in error and require modification. No treatment was made of armature time constants during this type of fault.

In this paper a semi-empirical method is presented for deriving the short-circuit and synchronizing-torque equations, using the method of symmetrical components. The equations are valid only to the extent that the assumptions made in their derivations are valid.

Basic Assumptions

In the first approach to the problem it is necessary to make certain simplifying assumptions in regard to the arrangement and electrical characteristics of the component parts of the machine. The closeness of agreement between assumed and actual conditions will determine how nearly the computed and actual performances of the machine will compare. A synchronous machine idealized to the following extent will be considered:

A. The air gap is uniform. The presence of slots on the quadrature axis of the machine and none on the direct axis does not invalidate this assumption to any great extent.

B. Saturation and hysteresis are neglected in calculating the alternating components of torque.

C. The field has distributed symmetrical windings on both axes. During the subtransient period this assumption is justified. In the actual machine there is no winding on the quadrature axis. However, the transient reactance on both axes are usually sufficiently close together to justify this assumption.

D. The stator has a sinusoidally distributed three-phase winding.

E. The air-gap flux is sinusoidally distributed in space.

Short-Circuit Torques

When the armature is short-circuited, there is trapped in the armature circuit a portion of normal armature flux, that portion being dependent upon the time of application and the type of short circuit. The decay of the trapped flux depends upon the time constant of the armature circuit containing the flux. It is this flux which manifests itself as a d-c component in the short-circuit current. If the short circuit is unbalanced, the armature current will contain, in addition to the d-c component, positive- and negative-sequence components of fundamental frequency. These components of current will set up positive- and negative-sequence armature magnetomotive forces and, neglecting saturation, positively and negatively rotating fields. The sudden appearance of the positive-sequence armature magnetomotive force over the direct axis of the rotor causes the rotor currents to rise suddenly, counterbalancing this additional direct-axis excitation. This follows from the fact that the flux linking the rotor circuits cannot change instantly. The additional rotor currents, induced by the sudden appearance of the positive-sequence field, are unsupported by exciter voltage and they decay with decrements which are dependent upon the short-circuit rotor time constants and the type of fault. The net excitation on the direct axis decays and, as a consequence, the air-gap flux also decays. This subject is treated very thoroughly in the papers of Doherty and Nickle.[6,7]

The alternating torque acting on the rotor (and also the stator) is proportional to the product of rotor and stator fields times the sine of the angle between them, thus there will be only fundamental-frequency and second-harmonic alternating torques. The fundamental-frequency torque results from the interaction of the unidirectional-armature field with the rotor field and the second-harmonic torque results from the interaction of the negative-sequence armature field with the rotor field. It can be shown[8] that these two components can be calculated by taking the sum of the instantaneous-phase powers as determined by the product of induced-phase voltage and instantaneous-armature current.

In addition to these alternating torques, there are also present unidirectional torques caused by losses in the machine. However, not all the ohmic losses will appear as torque. It is possible to determine (neglecting windage and friction) the unidirectional torque from the general relation applied to the average power.

Power output equals power input to the shaft plus the rate of decrease of stored kinetic energy in the machine plus the rate of decrease of stored magnetic energy in the machine minus the total ohmic losses in the machine. The sum of the first two terms on the right-hand side of the equation are proportional to the unidirectional torque acting on the rotor (the changes in rotor velocity are usually quite small). During a short circuit, the power output is zero and the unidirectional torque is equal to the sum of the average ohmic losses minus the rate of decrease of average stored magnetic energy in the machine. In other words, some of the ohmic losses are supplied by

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H. S. KIRSCHBAUM is central station engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

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decaying magnetic fields. Of the losses in the machine, two components are so supplied; the loss caused by the flow of direct current in the short-circuited armature, and the loss caused by the flow of the additional direct current in the rotor circuits. The remainder of the d-c ohmic loss in the rotor field is supplied by the exciter. Therefore, the only machine losses which appear as unidirectional torque are those which are caused by the flow of alternating current in the various machine circuits.

Assuming a solid rotor structure, the rotor resistance and reactance vary very closely as the square root of the frequency of the rotor current.[8] At double frequency the rotor resistance is $\sqrt{2}$ times as great as it is at fundamental frequency. If R_2 is the negative-sequence resistance of the machine as measured with double-frequency rotor currents flowing, the rotor resistance is $2(R_2-R_1)$ at double frequency and at fundamental frequency it is $\sqrt{2}(R_2-R_1)$. In turbine generators, it has been determined that the rotor losses vary very closely as the 1.8 power of the rotor current.[9] Since the rotor circuits are assumed to be identical on both axes of the rotor, the rotor currents will be balanced polyphase currents and there will be no second- or fourth-harmonic components of rotor loss; only the average loss will appear. Because transients of short duration in the rotor body are neglected, the rotor-loss torques appear as a suddenly applied unidirectional torque. The ohmic loss resulting from the flow of 60-cycle current in the stator has a double-frequency component during unbalanced short circuits. This double-frequency torque is usually negligible in comparison with the other alternating torques present during the short circuit, hence only the average value of this loss is retained in the computation of the unidirectional component. The total alternating- and unidirectional-rotor torques are derived for the line-to-line-to-line short circuit in Appendix II.

Table I

Type of Fault	Short-Circuit Torque
Line-to-ground on phase a	$T=\frac{E^2}{(X_d''+X_2+X_0)}\left[2FA\sin(\omega t+\alpha)-F^2\sin 2(\omega t+\alpha)\right]+2\left[\frac{EF}{X_d''+X_2+X_0}\right]^{1.8}\cdot(R_2-R_1)+\sqrt{2}\left[\frac{\sqrt{2}EA}{X_d''+X_2+X_0}\right]^{1.8}(R_2-R_1)+3\left[\frac{EF}{X_d''+X_2+X_0}\right]^{3}R_1$ per unit torque $F=\left[\frac{X_d''+X_2+X_0}{X_d+X_2+X_0}+\frac{(X_d''+X_2+X_0)(X_d-X_d')}{(X_d'+X_2+X_0)(X_d+X_2+X_0)}\epsilon^{-\frac{t}{T_{do'}}\frac{X_d+X_2+X_0}{X_d'+X_2+X_0}}+\frac{(X_d'-X_d'')}{(X_d'+X_2+X_0)}\epsilon^{-\frac{t}{T_{do''}}\frac{X_d'+X_2+X_0}{X_d''+X_2+X_0}}\right]$ $A=(\cos\alpha)\epsilon^{-2\pi f\frac{3R_a}{X_d''+X_2+X_0}t}$, α = angle between direct axis of rotor and phase a
Line-to-line on phases b to c	$T=\frac{E^2}{(X_d''+X_2)}\left[2FA\sin(\omega t+\alpha)-F^2\sin 2(\omega t+\alpha)\right]+2\left[\frac{EF}{X_d''+X_2}\right]^{1.8}(R_2-R_1)+\sqrt{2}\left[\frac{\sqrt{2}EA}{X_d''+X_2}\right]^{1.8}(R_2-R_1)+2\left[\frac{EF}{X_d''+X_2}\right]^{2}R_1$ per unit torque $F=\left[\frac{X_d''+X_2}{X_d+X_2}+\frac{(X_d''+X_2)(X_d-X_d')}{(X_d'+X_2)(X_d+X_2)}\epsilon^{-\frac{t}{T_{do'}}\frac{X_d+X_2}{X_d'+X_2}}+\frac{(X_d'-X_d'')}{(X_d'+X_2)}\epsilon^{-\frac{t}{T_{do''}}\frac{X_d'+X_2}{X_d''+X_2}}\right]$ $A=(\cos\alpha)\epsilon^{-2\pi f\frac{2R_a}{X_d''+X_2}t}$, α = angle between quadrature axis of rotor and phase a
Three phase	$T=\frac{E^2}{X_d''}FA\sin\omega t+\sqrt{2}\left[\frac{\sqrt{2}EA}{2X_d''}\right]^{1.8}\cdot(R_2-R_1)+\left[\frac{EF}{X_d''}\right]^{2}R_1$ per unit torque $F=\left[\frac{X_d''}{X_d}+\frac{X_d''(X_d-X_d')}{X_d'X_d}\epsilon^{-\frac{t}{T_{do'}}\frac{X_d}{X_d'}}+\frac{(X_d'-X_d'')}{X_d'}\epsilon^{-\frac{t}{T_{do''}}\frac{X_d'}{X_d''}}\right]$ $A=\epsilon^{-2\pi f\frac{R_a}{X_d''}t}$
Line-to-line-to-ground on phases b and c	$T=\frac{E^2}{\left[X_d''+\frac{X_2X_0}{X_2+X_0}\right]}\left[2A_1F\sin(\omega t+\alpha)-2A_2F\cos(\omega t+\alpha)-F^2\frac{X_0}{X_2+X_0}\sin 2(\omega t+\alpha)\right]+2\left[\frac{EF}{X_d''+X_2+\frac{X_d''X_2}{X_0}}\right]^{1.8}\cdot(R_2-R_1)+\sqrt{2}\left\{\left[\frac{\sqrt{2}EA_1}{X_d''+\frac{X_2X_0}{X_2+X_0}}\right]^{1.8}+\left[\frac{\sqrt{2}EA_2}{X_d''+\frac{X_2X_0}{X_2+X}}\right]^{1.8}\right\}\times(R_2-R_1)+2\left[\frac{EF\sqrt{X_2^2+X_2X_0+X_0^2}}{X_d''X_2+X_2X_0+X_0X_d''}\right]^{2}R_1$ per unit torque $F=\left[\frac{X_d''X_2+X_2X_0+X_0X_d''}{X_dX_2+X_2X_0+X_0X_d}+\frac{(X_d''X_2+X_2X_0+X_0X_d'')(X_2+X_0)(X_d-X_d')}{(X_d'X_2+X_2X_0+X_0X_d')(X_dX_2+X_2X_0+X_0X_d)}\epsilon^{-\frac{t}{T_{do'}}\frac{X_dX_2+X_2X_0+X_0X_d}{X_d'X_2+X_2X_0+X_0X_d'}}+\frac{(X_2+X_0)(X_d'-X_d'')}{(X_d'X_2+X_2X_0+X_0X_d')}\epsilon^{-\frac{t}{T_{do''}}\frac{X_d'X_2+X_2X_0+X_0X_d'}{X_d''X_2+X_2X_0+X_0X_d''}}\right]$ $A_1=\left[\frac{(X_2+2X_0)\cos\alpha}{2(X_2+X_0)}\right]\epsilon^{-2\pi f\frac{2R_a}{X_d''+X_2}t}$, $A_2=\left[\frac{X_2\sin\alpha}{2(X_2+X_0)}\right]\epsilon^{-2\pi f\frac{4R_a}{X_d''+X_2+4X_0}t}$, α = angle between quadrature axis of rotor and phase a

Table II

Type of Synchronizing	Synchronizing Torques
Three phase	$T=\frac{E^2 \sin \delta}{(X_d''+X_3)}\left[1-\cos \omega t+\tan \frac{\delta}{2} \sin \omega t\right]$
Single phase (a phase not connected)	$T=\frac{E^2 \sin \delta}{(X_d''+X_3+2X_2)}\left[1-\cos 2(\omega t+\alpha)-\tan \frac{\delta}{2} \sin 2(\omega t+\alpha)-\frac{2 \sin\left(\frac{\alpha+\beta}{2}\right)}{\cos\left(\frac{\alpha-\beta}{2}\right)} \sin (\omega t+\alpha)\right]$

$e_a=E \cos (\omega t+\alpha)$, $e_b=E \cos (\omega t+\beta)$, $\delta=(\alpha-\beta)$

Decrements

The subject of rotor and armature decrements has been very ably handled elsewhere for single-phase and three-phase faults and will not be discussed here.[8,7] However, except for the work of Smith and Weygandt,[12] the armature decrements for the double-line-to-ground fault have not been treated as extensively. Because the armature has two coupled circuits which are short-circuited, the direct currents in the armature will, in general, have two decrements. Therefore, there will be two decrements on the fundamental-frequency rotor torque and on the unidirectional torque resulting from the flow of fundamental-frequency current in the rotor. These decrements are derived in Appendix III, however space does not permit the full derivation of the rotor torques during a double-line-to-ground fault.

External Impedance

If the external impedance is predominantly reactance (or resistance so low as not to affect the short-circuit current) the torques can be calculated from the equations in Table I by replacing the machine reactances by the total reactances in the various sequence networks. In calculating the loss torques (R_3-R_1) will remain unchanged but R_1 in the calculation of the stator loss must be replaced by (R_1+R_a). In the factor A, R_a is replaced by (R_a+R_a') where R_a' is the d-c resistance per phase of the external impedance.

If the external impedance is predominantly resistance of a large enough magnitude to affect the fault current, the time constants of the fundamental-frequency torque and the unidirectional torque resulting from the flow of fundamental-frequency current in the rotor will be very low (in the order of one or two cycles or less). In most cases these components may be neglected in calculating shaft stresses. The stator loss, which will be quite high, has time constants which are determined by the decay of rotor flux, and for external resistances in the order of subtransient reactance the rotor time constants are but little affected by the presence of the external resistance. The methods which have been presented in Appendixes II and III can be extended to the calculation of faults containing appreciable resistance by the inclusion of the resistance in the sequence networks. This type of fault is of importance in those types of mechanical systems where the contribution of the unidirectional torque to shaft torque is appreciable. This is discussed at greater length in a companion paper.[10]

Short Circuits From Load

It is more probable for a short circuit to occur from load than from no load, but for this condition the equations of Table I can be applied by making several approximations. The alternating components of torque can be calculated fairly accurately by using the derived equations with the voltage behind subtransient reactance. When the short circuit is three phase, the entire external load is dropped and the only unidirectional torque will be that given by the equations in Table I. This is also true in the case of a double-line-to-ground fault on a machine with very low zero-sequence reactance.

Assuming a static load, the machine will rapidly drop about a half load on a line-to-line fault. In this case, the total unidirectional torque on the machine is the sum of the loss torque plus half the initial load on the machine. On a line-to-ground fault, the amount of load dropped will depend upon the zero-sequence reactance of the machine but may be calculated by symmetrical components. The remaining load is then added to the loss torque to get the total unidirectional torque. In both of these cases, the load which the machine carries will have a decrement equal to the decrement of the ohmic loss in the machine. In a companion paper[10] the effect of short circuiting the machine from load is discussed in relation to the resultant stresses.

Synchronizing

If a machine is synchronized considerably out of phase with a low-reactance system, the resulting torques may reach values greater than those encountered during a short circuit. If the synchronizing takes place with all three circuit-breaker poles closing at the same in-

Table III

Type of Short Circuit	Unidirectional Torque	Sin $(\omega t+\alpha)$	Cos $(\omega t+\alpha)$	Sin $2(\omega t+\alpha)$
Three phase, $R_a=0$	$1.54e^{-7.93t}$	$10.3e^{-10.2t}$	Negligible	0
Three phase, $R_a=0.01$	$1.57e^{-10.2t}+1.03e^{-78t}$	$10.3e^{-48.5t}$	Negligible	0
Line to line, $R_a=0$, $\alpha=0°$	$2.07e^{-8.93t}$	$10.4e^{-8.93t}$	Negligible	$-5.18e^{-8.93t}$
Line to line, $R_a=0.01$, $\alpha=0°$	$1.58e^{-8.93t}+1.03e^{-78t}$	$10.4e^{-48.9t}$	Negligible	$-5.18e^{-8.93t}$
Line to ground, $R_a=0$, $\alpha=0°$	$1.88e^{-7.93t}$	$9.50e^{-8.93t}$	Negligible	$-4.75e^{-8.34t}$
Line to ground, $R_a=0.01$, $\alpha=0°$	$1.66e^{-8.18t}+0.89e^{-107t}$	$9.50e^{-83t}$	Negligible	$-4.75e^{-8.34t}$
Double line to ground, $R_a=0$, $\alpha=0°$	$1.77e^{-8.93t}$	$10.4e^{-8.81t}$	Negligible	$-1.39e^{-8.93t}$
Double line to ground, $R_a=0.01$ $\alpha=0°$,	$2.14e^{-8.93t}+1.02e^{-77.5t}$	$10.4e^{-47.7t}$	Negligible	$-1.39e^{-8.93t}$
Double line to ground, $R_a=0$ $\alpha=90°$,	$1.33e^{-13.5t}$	Negligible	$-7.54e^{-13.5t}$	$-1.39e^{-8.93t}$

Machine constant	X_d''	X_d'	X_d	X_3	X_2	T_{do}''	T_{do}'	R_1	R_2	R_a
Value (per unit)	0.097	0.152	1.170	0.096	0.0177	0.055 sec.	6.65 sec.	0.00480	0.0250	0.00105

stant, there will exist unidirectional synchronizing and loss torques and, in addition, a fundamental-frequency torque resulting from the trapped armature flux. However, if only two of the poles close (the other pole not closing at all), there will be, in addition to the above torques, a double-frequency torque developed by the negative-sequence armature current.

Because of the complexity of the synchronizing problem, additional simplifying assumptions have been made to supplement those already made.

For faulty synchronizing, the loss torque is generally much less than the synchronizing torques and may be neglected.

If synchronization takes place with the machine either leading or lagging the system, the armature current will have a direct axis component which will tend to demagnitize the main poles causing the direct axis rotor flux to decay. This results in the problem of calculating the current in a circuit having one voltage fixed (the source) and one voltage varying with time (the internal machine voltage). Since, in a great many mechanical systems, the maximum stresses are reached in the first or second cycle, the problem can be greatly simplified by neglecting the rotor decrements.

Finally, it is assumed that the angle between the system and machine remains sufficiently unchanged during the first two or three cycles to permit the calculation of the synchronizing currents without having to take into account the oscillation of the machine with respect to the system.

In Appendix IV the synchronizing-torque equation is derived on the above assumptions for single-phase synchronizing. The torque equations presented in Table II are applicable to only the first two or three cycles of the synchronization. If it is desired to calculate the torque beyond two or three cycles, the decrements of rotor flux may be included as shown under short-circuit torques.

Illustrations

In Table III there are listed the various torque components for a typical turbine generator short-circuited from no load. The tabulation includes short circuits with and without an external resistance of 0.01 per unit. The field-decrement factor was calculated using an average decrement which gave the correct initial and sixth-cycle values. This is pessimistic but, as shown by McCann, Warren, and Criner,[10] the shaft torques are but slightly affected using this approximation. In those cases where the fault was through an external resistance, the loss torques contained two components with such widely different decrements that they were not combined as above.

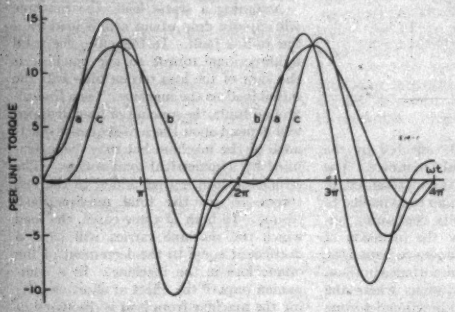

Figure 1. Short-circuit and synchronizing torques

(a). Line-to-line short circuit, $\alpha = 0°$

(b). Three-phase synchronizing, $\delta = 90°$, $X_s = X_d''$

(c). Single-phase synchronizing, $\delta = 90°$, $\alpha = 135°$, $\beta = 45°$, $X_s = X_d''$

In Figure 1 there are shown the electrical torques for a line-to-line short circuit and two conditions of synchronizing. Although the three-phase synchronizing torque does not reach as high a peak as the line-to-line short-circuit torque, its components are only unidirectional and fundamental-frequency ones. These components will produce much more serious shaft stress than would second-harmonic torque. As shown in Figure 2 (which was plotted for the same machine as in Table III) synchronizing considerably out of phase is especially dangerous. The peak shaft torque will be approximately proportional to the peak electrical torque. All other conditions being equal, the electrical torque for single-phase synchronizing (only two poles closing) is not as severe as for three-phase synchronizing.

Conclusions

As a result of the analysis made in this paper the following conclusions can be drawn regarding the various factors affecting transient torques in synchronous machines.

Short circuits on low-reactance turbine generators will produce electrical torques acting on the rotor which may reach peaks of 15 to 20 times normal torque.

The effect of external resistance during a fault is twofold, the unidirectional torque is increased, and the decrement of the fundamental-frequency torque is also increased. This may, or may not, result in increased shaft stress, depending upon the masses and spring constants of the turbine generator.

The negative-sequence resistance of the machine is a very important constant in determining the unidirectional torque during unbalanced faults. At the present time this constant is not known very accurately for values of rotor current in the order of short-circuit currents.

Synchronizing out of phase can produce electrical torques in excess of those encountered during short circuit. This is especially true for low-reactance machines connected to low-reactance systems.

Appendix I. List of Symbols

Per phase machine constants (all constants are per unit unless noted otherwise):

X_d''—Direct-axis subtransient reactance
X_d'—Direct-axis transient reactance
X_d—Direct-axis synchronous reactance
X_2—Negative-sequence reactance
X_0—Zero-sequence reactance
L—Self-leakage inductance of any stator phase
M—Mutual inductance between any two stator phases
R_1—Positive-sequence resistance

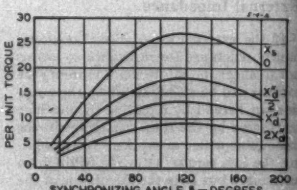

Figure 2. Crest electrical torque during three-phase synchronizing as a function of synchronizing angle and system reactance

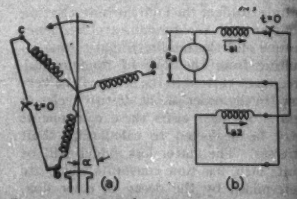

Figure 3. Line-to-line short circuit on a synchronous machine

R_2—Negative-sequence resistance

R_a—D-c resistance of stator

T_{da}''—Subtransient-open-circuit time constant in direct axis—seconds

T_{da}'—Transient-open-circuit time constant in direct axis—seconds

Machine and system quantities (per unit unless noted otherwise):

e—Instantaneous machine (or system) voltage

i—Instantaneous-phase current

E—Effective machine (or system) voltage

X_s—System reactance

R_s—External resistance

α, β, δ—Angles defined in Tables I and II

f—Fundamental frequency in cycles per second

$\omega = 2\pi f$

t—Time in seconds after the initiation of the circuit transient

Appendix II. Line-to-Line Short Circuit

During a line-to-line short circuit, Figure 3a, the alternating armature currents can be calculated by using the method of symmetrical components. With the positive- and negative-sequence networks connected as shown in Figure 3b, the sequence components of armature current can be determined, and from these the armature current.

The instantaneous voltage of phase a before the short circuit is

$$e_a = E\cos(\omega t+\alpha)$$

This voltage is proportional to the rotor flux, which, after the short circuit, decays because of the demagnetizing effect of the armature current. The decrement factor for this flux has been derived by Doherty and Nickle and is

$$F = \frac{X_d''+X_2}{X_d+X_2} + \frac{(X_d''+X_2)(X_d-X_d')}{(X_d'+X_2)(X_d+X_2)}\epsilon^{-\frac{t}{T_{da}'}\frac{X_d+X_2}{X_d'+X_2}} + \frac{(X_d'-X_d'')}{(X_d'+X_2)}\epsilon^{-\frac{t}{T_{da}''}\frac{X_d'+X_2}{X_d''+X_2}} \quad (1)$$

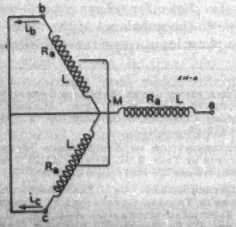

Figure 4. Flow of direct current in the armature of a synchronous machine during a double-line-to-ground fault

$$L \doteq \frac{1}{3}[X_d''+X_2+X_0] \text{ in per unit}$$

$$M \doteq \frac{1}{6}[X_d''+X_2-2X_0] \text{ in per unit}$$

The a-c symmetrical components of current are

$$i_{a1} = -i_{a2} = \frac{EF\sin(t+\alpha)}{(X_d''+X_2)} \text{ instantaneous per unit amperes} \quad (2)$$

From these, the alternating phase currents are

$$i_b = -i_c = \frac{-\sqrt{3}EF\cos(t+\alpha)}{(X_d''+X_2)} \text{ instantaneous per unit amperes} \quad (3)$$

At zero time, the phase current must be zero, therefore, there is in each phase a d-c component of current which has a decrement determined by the armature circuit.

The total phase currents are

$$i_b = -i_c = \frac{\sqrt{3}E}{(X_d''+X_2)}[A - F\cos(\omega t+\alpha)] \quad (4)$$

where

$$A = (\cos\alpha)\epsilon^{-2\pi f\frac{2R_a}{X_d''+X_2}t} \quad (5)$$

The power transferred across the air gap can be determined by taking the sum of the instantaneous products of the phase currents and phase voltages.

$$P = \frac{2}{3}[i_a e_a + i_b e_b + i_c e_c] \quad (6)$$

$$P = \frac{2}{3}[0 + i_b(e_b - e_c)] = \frac{2}{3}\frac{\sqrt{3}E}{(X_d''+X_2)}\times [A - F\cos(\omega t+\alpha)]\sqrt{3}EF\sin(\omega t+\alpha) \quad (7)$$

$$P = \frac{E^2}{(X_d''+X_2)}[2AF\sin(\omega t+\alpha) - F^2\times \sin 2(\omega t+\alpha)] \quad (8)$$

In per unit, the torque acting in the rotor is equal to the power transferred across the air gap.

The unidirectional torque acting on the rotor can be written as the sum of the a-c ohmic losses in the machine. The initial unidirectional field has twice the value that the initial negative-sequence field has, resulting in equal induced rotor voltages. Since the impedance of the solid rotor varies very closely as the square root of frequency, the fundamental-frequency rotor currents are $\sqrt{2}$ times the second-harmonic rotor currents. Because of the effect of rotor saturation on the depth of current penetration in the rotor, the rotor losses vary as the 1.8 power of the rotor current.

The a-c ohmic losses in the machine are

$$P_L = 2\left[\frac{EF}{X_d''+X_2}\right]^{1.8}(R_2 - R_1) + \sqrt{2}\left[\frac{\sqrt{2}EA}{X_d''+X_2}\right]^{1.8}(R_2 - R_1) + 2\left[\frac{EF}{X_d''+X_2}\right]^2 R_1 \quad (9)$$

The total torque acting on the rotor is

$$T = \frac{E^2}{(X_d''+X_2)}[2FA\sin(\omega t+\alpha) - F^2\sin 2(\omega t+\alpha)] + 2\left[\frac{EF}{X_d''+X_2}\right]^{1.8}\times (R_2 - R_1) + \sqrt{2}\left[\frac{\sqrt{2}EA}{X_d''+X_2}\right]^{1.8}(R_2 - R_1) + 2\left[\frac{EF}{X_d''+X_2}\right]^2 R_1 \quad (10)$$

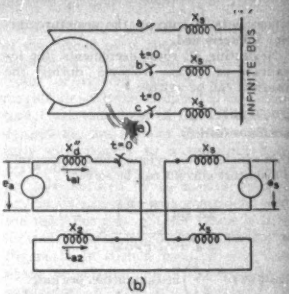

Figure 5. Single-phase synchronizing

Appendix III. Armature Decrements During Double-Line-to Ground Fault

The machine windings have approximately the self-leakage and mutual reactances shown in Figure 4.

The differential equations for the direct armature currents can be written as follows:

$$\begin{cases}(R_a+Lp)i_b - (Mp)i_c = 0 & (11)\\ -(Mp)i_b + (R_a+Lp)i_c = 0 & (12)\end{cases}$$

from which the determinental equation can be written

$$D(p) = (R_a+Lp)^2 - (Mp)^2 = 0 \quad (13)$$

The roots of this equation will give the decrements of the d-c components of armature current. They are

$$p_1 = -\frac{R_a}{(L+M)} = -\frac{2R_a}{X_d''+X_2} \text{ in per unit} \quad (14)$$

$$p_2 = -\frac{R_a}{(L-M)} = -\frac{6R_a}{X_d''+X_2+4X_0} \text{ in per unit} \quad (15)$$

Converting to second instead of per unit time measure, the direct currents generally will have the following forms

$$i_b = A_1\epsilon^{-2\pi f\frac{2R_a}{X_d''+X_2}t} + A_2\epsilon^{-2\pi f\frac{6R_a}{X_d''+X_2+4X_0}t} \quad (16)$$

$$i_c = A_3\epsilon^{-2\pi f\frac{2R_a}{X_d''+X_2}t} + A_4\epsilon^{-2\pi f\frac{6R_a}{X_d''+X_2+4X_0}t} \quad (17)$$

where the constants can be determined by initial conditions.

Appendix IV. Single-Phase Synchronizing Out of Phase

During single-phase synchronizing, Figure 5a, the sequence components of armature currents can be found by connecting the sequence networks as in Figure 5b. From the positive- and negative-sequence

components of current, the armature current is determined.

Neglecting all rotor decrements, the instantaneous phase voltages during the transient can be written

$$e_a = E\cos(\omega t+\alpha)$$
$$e_b = E\cos(\omega t+\beta)$$

from which the a-c symmetrical components of armature current can be solved.

$$i_{ac} = -i_{ac} = -\frac{2E\sin\left(\frac{\alpha-\beta}{2}\right)}{(X_d''+X_2+2X_a)}\times \cos\left(\omega t+\frac{\alpha+\beta}{2}\right) \text{ instantaneous per unit amperes} \quad (18)$$

The alternating phase currents are

$$i_b = -i_c = -\frac{2\sqrt{3}\,E\sin\left(\frac{\alpha-\beta}{2}\right)}{(X_d''+X_2+2X_a)}\times \sin\left(\omega t+\frac{\alpha+\beta}{2}\right) \quad (19)$$

Since the currents must start from zero, there is a d-c component present in the current. The total phase currents are therefore

$$i_b = -i_c = -\frac{2\sqrt{3}E\sin\left(\frac{\alpha-\beta}{2}\right)}{(X_d''+X_2+2X_a)}\times \left[\sin\left(\omega t+\frac{\alpha+\beta}{2}\right)-\sin\left(\frac{\alpha+\beta}{2}\right)\right] \quad (20)$$

The instantaneous power is

$$P = \frac{2}{3}\left[i_a e_a + i_b e_b + i_c e_c\right] \quad (21)$$

$$P = \frac{2}{3}\left[i_b(e_b-e_c)\right] = \frac{2}{3}\,\frac{2\sqrt{3}E\sin\left(\frac{\alpha-\beta}{2}\right)}{(X_d''+X_2+2X_a)}\times \left[\sin\left(\omega t+\frac{\alpha+\beta}{2}\right)-\sin\left(\frac{\alpha+\beta}{2}\right)\right]\times \sqrt{3}E\sin(\omega t+\alpha) \quad (22)$$

Since in per unit the rotor torque is equal to the power transferred across the gap

$$T = P = \frac{E^2\sin\delta}{(X_d''+X_2+2X_a)}\left[1-\cos 2(\omega t+\alpha)-\tan\frac{\delta}{2}\sin 2(\omega t+\alpha)-2\,\frac{\sin\left(\frac{\alpha+\beta}{2}\right)}{\cos\left(\frac{\alpha-\beta}{2}\right)}\times \sin(\omega t+\alpha)\right] \quad (23)$$

where

$$\delta = (\alpha-\beta) \quad (24)$$

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Measurement of the Subtransient Impedances of Synchronous Machines

GORDON F. TRACY
ASSOCIATE AIEE

WILLIAM F. TICE
NONMEMBER AIEE

A METHOD of measuring the direct-axis and the quadrature-axis subtransient impedances of a synchronous motor or generator by impressing three-phase voltages on the machine at standstill is described in this paper. With respect to the two methods at present prescribed in the Test Code for Synchronous Machines and elsewhere,[1,2,3] the proposed method for measuring the subtransient impedances has the advantages that it does not involve the taking of oscillograms and the consequent uncertainties in their analyses, nor does it require that the rotor of the machine under test be set in certain definite positions. This latter requirement, called for in the single-phase test, is frequently troublesome, particularly if the machine is large. Moreover, as three-phase, rather than single-phase voltages are impressed, the measurements are made under conditions more nearly simulating those of normal operation

The proposed method consists, briefly, of making two tests on the machine at standstill with the rotor in any position whatsoever. In the first test a three-phase voltage is impressed on the stator terminals and appropriate instrument readings are taken from which the positive-sequence and negative-sequence components of both the voltage and the current are obtained. In the second test a single-phase alternating voltage is applied to the field terminals with the stator terminals disconnected, readings being taken of the corresponding voltages induced in the stator. This latter test yields the angular position of the field structure with respect to the reference phase. The data obtained from these tests are then substituted into two equations, shown later in this paper as equations 37 and 38, which yield the subtransient impedances.

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G. F. Tracy is associate professor of electrical engineering, University of Wisconsin, Madison, Wis., and W. F. Tice is with the Barber-Colman Company, Rockford, Ill.

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Development of the Equations

Rotor Magnetomotive Forces

The basic principles of this development were suggested by a paper on the calculation of the starting characteristics of synchronous motors by H. V. Putman.[4] The general case of a cylindrical rotor carrying an unbalanced two-phase winding and a stator carrying a balanced three-phase winding will first be discussed, then the treatment will be modified to apply to a synchronous machine.

In Figure 1a the conductors A and A' represent one phase of the rotor while B and B' represent the other phase. These two windings are assumed to be unbalanced, not only with respect to their impedances, but also with respect to the number of turns in each. In addition, the magnetic axes are not 90 degrees apart. The magnetic axis of stator phase a is also shown for reference purposes.

Due to the unbalance of the rotor, the three-phase input currents are unbalanced

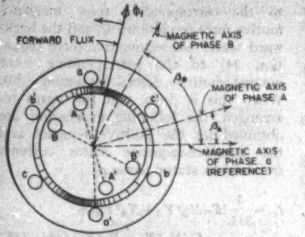

Figure 1a. Cylindrical-rotor machine with balanced three-phase stator and unbalanced two-phase rotor

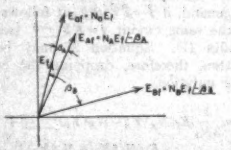

Figure 1b. Vector diagram showing relative phase positions of voltages due to forward flux

and are considered, therefore, to consist of a positive-sequence and a negative-sequence set of components. Corresponding to the positive-sequence currents is a forward-rotating magnetomotive force and air-gap flux, and corresponding to the negative-sequence currents is a backward-rotating magnetomotive force and air-gap flux. These two air-gap fluxes are considered to be constant in magnitude as they rotate, and, at standstill, they rotate forward and backward, respectively, at synchronous speed.

Two voltages, corresponding to the two components of air-gap flux, are induced in each rotor phase. Let E_{Af} be the voltage induced in phase A by the forward flux and E_{Ab} be that induced in phase A by the backward flux. Since the rotor circuits are closed each voltage produces a current. In phase A these currents will be designated by I_{Af} and I_{Ab}. Each current, in turn, sets up a magnetomotive force which alternates along the magnetic axis of the phase. Using a well-known analysis, the space fundamental of each magnetomotive force may be replaced by two component traveling space sinusoids moving in opposite directions at synchronous speed, each having an amplitude equal to one-half of the peak amplitude of the original magnetomotive force. The vector expression for the forward-moving component of magnetomotive force due to I_{Af} is†

$$M_{Af}' = -j\,0.9\,N_A I_{Af}/\beta_A \quad (1)$$

† See Appendix I for the derivation of equations 1 and 2.

while that for the backward-moving component of magnetomotive force due to I_{Af} is

$$M_{Af}'' = +j\,0.9\,N_A I_{Af}/\beta_A \quad (2)$$

where

N_A = effective turns in phase A (including pitch and breadth factors).
I_{Af} = vector value* of I_{Af}.
$\hat{I}_{Af}$ = conjugate of I_{Af}.
β_A = angle of displacement of rotor phase A from the reference axis.

In equations 1 and 2, as well as all which follow, the single prime indicates a forward-rotating magnetomotive force and the double prime indicates a backward-rotating magnetomotive force. The subscripts refer to the current component producing the magnetomotive force; the first indicating the phase, and the second showing whether produced by the forward or the backward flux.

Two expressions, similar to equations 1 and 2, may be written for the magnetomotive force components due to current I_{Ab} in phase A corresponding to the backward flux. Likewise, four more expressions may be written for the magnetomotive force components due to the currents in phase B. There will be a total, therefore, of eight traveling waves of magnetomotive force, four moving forward along the air gap at synchronous speed and four moving backward at synchronous speed.

Before finding the resultant magnetomotive force it is convenient to express each current in terms of the corresponding voltage and the admittance of the circuit on which the voltage acts. Since, in general,

$$I = EY, \quad (3)$$

and**

$$\hat{I} = \hat{E}\hat{Y} \quad (4)$$

equations 1 and 2 become

$$M_{Af}' = -j\,0.9\,N_A E_{Af} Y_A/\beta_A \quad (5)$$

$$M_{Af}'' = +j\,0.9\,N_A \hat{E}_{Af} \hat{Y}_A/\beta_A \quad (6)$$

The two components of phase A magnetomotive force corresponding to the backward flux are

$$M_{Ab}' = -j\,0.9\,N_A E_{Ab} Y_A/\beta_A \quad (7)$$

$$M_{Ab}'' = +j\,0.9\,N_A \hat{E}_{Ab} \hat{Y}_A/\beta_A \quad (8)$$

The four components of phase B magnetomotive force are

$$M_{Bf}' = -j\,0.9\,N_B E_{Bf} Y_B/\beta_B \quad (9)$$

$$M_{Bf}'' = +j\,0.9\,N_B \hat{E}_{Bf} \hat{Y}_B/\beta_B \quad (10)$$

$$M_{Bb}' = -j\,0.9\,N_B E_{Bb} Y_B/\beta_B \quad (11)$$

$$M_{Bb}'' = +j\,0.9\,N_B \hat{E}_{Bb} \hat{Y}_B/\beta_B \quad (12)$$

* A vector quantity is designated by a bold-face symbol and a conjugate is designated by a circumflex over the symbol.

** See Appendix II for verification of equation 4.

Since the forward flux, ϕ_f, is constant in magnitude as it rotates, the voltage induced by it in any turn of any winding (rotor or stator) will be identical in magnitude with that induced in any other turn; but the phase of the voltage will depend on the angular position of the turn with respect to a reference axis. Let E_f be the vector value of the voltage *per turn* induced by ϕ_f in any winding having its magnetic axis coincident with the reference axis. Stator phase a is so located. The forward flux is shown in Figure 1a in such a position that it is about to generate maximum voltage in conductors a and a'. Therefore the vector E_f, Figure 1b, will be nearly vertical at this instant. Later in time, when the forward flux has moved through β_A degrees, maximum voltage will be generated in rotor phase A. Hence the vector E_{Af} lags E_f by β_A degrees. Likewise E_{Bf} lags E_f by β_B degrees. The magnitude of each is equal to that of E_f multiplied by the respective number of turns. The voltages due to the forward flux, expressed in terms of E_f are

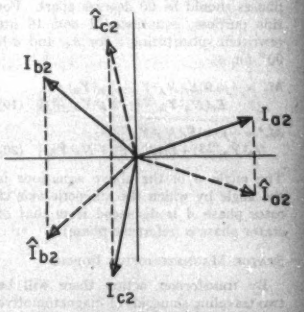

Figure 2. Relations between the negative-sequence currents and their conjugates

$$E_{Af} = N_A E_f/-\beta_A \quad (13)$$

$$E_{Bf} = N_B E_f/-\beta_B \quad (14)$$

Similarly,

$$E_{Ab} = N_A E_b/+\beta_A \quad (15)$$

$$E_{Bb} = N_B E_b/+\beta_B \quad (16)$$

where E_b is the vector value of the voltage per turn induced by the backward flux in any winding having its magnetic axis coincident with the reference axis.

The resultant forward rotor magnetomotive force is the vector sum of equations 5, 7, 9, and 11, and this sum is shown below after appropriate substitution of equations 13 to 16.

$$M_r' = -j\,0.9\,[E_f(N_A^2 Y_A + N_B^2 Y_B) + E_b(N_A^2 Y_A/2\beta_A + N_B^2 Y_B/2\beta_B)] \quad (17)$$

Similarly, the resultant backward rotor

magnetomotive force is the vector sum of equations 6, 8, 10, and 12, which, upon substitution of equations 13 to 16, yields:

$$M_r' = +j\,0.9[\underline{E_f}(N_A{}^2\underline{Y}_A/\underline{2\beta_A} + N_B{}^2\underline{Y}_B/\underline{2\beta_B}) + \underline{E_b}(N_A{}^2\underline{Y}_A + N_B{}^2\underline{Y}_B)] \quad (18)$$

It is to be observed, in making the substitutions leading to equation 18, that the conjugate of $\underline{E_f/-\beta_A}$ is $\underline{E_f/+\beta_A}$; that is, the reversal in sign applies not only to the angle included in the vector E_f but also to the attached angle $-\beta_A$.

While equations 17 and 18 are written for a rotor with only two phases, it is evident that they may be made to apply to a rotor with any number of phases by adding terms of the form $N_c{}^2\underline{Y_c}$, $N_c{}^2\times \underline{Y_c}\,\underline{/2\beta_c}$, and so forth. In applying this analysis to a synchronous machine, however, where phase A is to represent the direct-axis circuits and phase B the quadrature-axis circuits, only two phases are necessary, and the magnetic axes of these phases should be 90 degrees apart. For this purpose, equations 17 and 18 are rewritten substituting β for β_A, and $\beta+90°$ for β_B.

$$M_r' = -j0.9[\underline{E_f}(N_A{}^2\underline{Y}_A + N_B{}^2\underline{Y}_B) + \underline{E_b}(N_A{}^2\underline{Y}_A/\underline{2\beta} - N_B{}^2\underline{Y}_B/\underline{2\beta})] \quad (19)$$

$$M_r'' = +j0.9[\underline{E_f}(N_A{}^2\underline{Y}_A/\underline{2\beta} - N_B{}^2\underline{Y}_B/\underline{2\beta}) + \underline{E_b}(N_A{}^2\underline{Y}_A + N_B{}^2\underline{Y}_B)] \quad (20)$$

The angle β in the above equations is the angle by which the magnetic axis of rotor phase A is displaced from that of stator phase a (reference phase).

Stator Magnetomotive Forces

By transformer action there will be two traveling sinusoids of magnetomotive force produced by the stator, a forward-moving magnetomotive force corresponding to M_r' and a backward-moving magnetomotive force corresponding to M_r''. Since the stator windings are three-phase symmetrical windings, each traveling sinusoid is produced by a set of *balanced* currents in the stator windings; the first set being the positive-sequence set, and the second, the negative-sequence set.

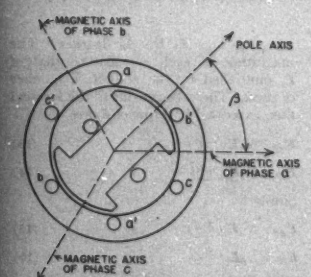

Figure 3. Synchronous machine with its pole axis displaced β degrees from the axis of phase a

Using the expressions for magnetomotive force as a space vector from Appendix I, the forward-rotating magnetomotive-force wave due to the positive-sequence currents in the stator is

$$M_s' = -j0.9(N_s\underline{I_{as}/0°} + N_s\underline{I_{bs}/120°} + N_s\underline{I_{cs}/240°}) \quad (21)$$

The angles shown in equation 21 express the direction in *space* of the magnetic axes of the three phases. In equation 21 substitute $\underline{I_{bs}} = \underline{I_{as}/-120°}$, and $\underline{I_{cs}} = \underline{I_{as}/-240°}$; also $N_a = N_b = N_c = N_s$ (effective stator turns per phase). Then

$$M_s' = -j0.9(3N_s\underline{I_{as}}) \quad (22)$$

The negative-sequence currents produce a backward magnetomotive force:

$$M_s'' = +j0.9N_s(\underline{I_{as}/0°} + \underline{I_{bs}/120°} + \underline{I_{cs}/240°}) \quad (23)$$

Since the conjugates of the currents are involved (see Figure 2)

$$\underline{I_{bs}} = \underline{I_{as}/-120} \text{ and } \underline{I_{cs}} = \underline{I_{as}/-240}$$

$$\therefore M_s'' = j0.9(3N_s\underline{I_{as}}) \quad (24)$$

Expressions 22 and 24 are similar to the familiar expression for the peak height of the fundamental of armature magnetomotive force of a three-phase winding, with the exception that 22 and 24 show not only the magnitudes but also the space positions of the peaks with respect to the magnetic axis of phase a.

Figure 5. Connection diagram for test II

A development, similar to that above, for the backward component of magnetomotive force due to the positive-sequence currents, and the forward component due to the negative-sequence currents, would yield zero in each case, as would be expected.

Stator-Current Equations

The next step is to equate the forward stator magnetomotive force (equation 22) to the corresponding rotor magnetomotive force (equation 19), and the backward stator magnetomotive force (equation 24) to the corresponding rotor magnetomotive force (equation 20). When this is done, and the terms rearranged, the following expressions are obtained for the positive-sequence and the negative-sequence stator currents (referred to stator phase a):

$$\underline{I_{as}} = \frac{1}{3N_s}[\underline{E_f}(N_A{}^2\underline{Y}_A + N_B{}^2\underline{Y}_B) + \underline{E_b}(N_A{}^2\underline{Y}_A - N_B{}^2\underline{Y}_B)/\underline{2\beta}] \quad (25)$$

$$\underline{I_{as}} = \frac{1}{3N_s}[\underline{E_f}(N_A{}^2\underline{Y}_A - N_B{}^2\underline{Y}_B)/\underline{2\beta} + \underline{E_b}(N_A{}^2\underline{Y}_A + N_B{}^2\underline{Y}_B)] \quad (26)$$

In general, if $\underline{I} = \underline{E}\underline{Y}/\underline{+\delta}$, it follows that in the same circuit $\underline{I} = \underline{E}\underline{Y}/\underline{-\delta}$ (see appendix II). Equation 26 may be rewritten, therefore, dropping the conjugate notation:

$$I_{as} = \frac{1}{3N_s}[E_f(N_A{}^2Y_A - N_B{}^2Y_B)/\underline{-2\beta} + E_b(N_A{}^2Y_A + N_B{}^2Y_B)] \quad (26a)$$

Equations 25 and 26a can be simplified by multiplying both sides of each by $2/N_s$. The admittances now appear as

$$\frac{2}{3}\frac{N_A{}^2}{N_s{}^2}Y_A \text{ and } \frac{2}{3}\frac{N_B{}^2}{N_s{}^2}Y_B$$

These are seen to be the values of the two rotor admittances referred to the stator. A further simplification is effected if the magnetizing reactance of each rotor phase, considered as a susceptance, be combined vectorially with the corresponding expression for rotor admittance, as in the equivalent circuit of a transformer. In Figure 1a, where the air gap is uniform, the magnetizing reactance is the same for both phases; but in the synchronous machine, shown in Figure 3, the magnetizing reactance along the pole axis is much larger than that along the interpolar axis. Let Y_A' and Y_B' be the admittances of phases A and B, respectively, referred to the stator, it being understood that each includes its own magnetizing reactance. Then

$$\underline{I_{as}} = \frac{N_s}{2}[\underline{E_f}(Y_A' + Y_B') + \underline{E_b}(Y_A' - Y_B')/\underline{2\beta}] \quad (27)$$

$$I_{as} = \frac{N_s}{2}[E_f(Y_A' - Y_B')/\underline{-2\beta} + E_b(Y_A' + Y_B')] \quad (28)$$

With Y_A' and Y_B' as defined above, I_{as} and I_{as} are the symmetrical components of the *total* input current including the magnetizing components.

The Stator-Voltage Equations

Defining V_1 and V_2 to be the positive-sequence and the negative-sequence components, respectively, of the line-to-neutral voltage impressed on stator

phase a, and Z_a to be the leakage impedance of phase a, then

$$V_1 = E_{af} + I_{a1}Z_a = N_1E_f + I_{a1}Z_a \quad (29)$$

$$V_2 = E_{ab} + I_{a2}Z_a = N_2E_b + I_{a2}Z_a \quad (30)$$

Solving for E_f and E_b from equations 27 and 28 and substituting in equations 29 and 30 yields

$$V_1 = I_{a1}\left(\frac{Y_A' + Y_B'}{2Y_A'Y_B'} + Z_a\right) + I_{a2}\left(\frac{Y_B' - Y_A'}{2Y_A'Y_B'}\right)\underline{/2\beta} \quad (31)$$

$$V_2 = I_{a1}\left(\frac{Y_B' - Y_A'}{2Y_A'Y_B'}\right)\underline{/-2\beta} + I_{a2}\left(\frac{Y_A' + Y_B'}{2Y_A'Y_B'} + Z_a\right) \quad (32)$$

But

$$\frac{Y_A' + Y_B'}{2Y_A'Y_B'} = \frac{1}{2}(Z_A' + Z_B')$$

and

$$\frac{Y_B' - Y_A'}{2Y_A'Y_B'} = \frac{1}{2}(Z_A' - Z_B')$$

Therefore

$$V_1 = I_{a1}\left(\frac{Z_A' + Z_B'}{2} + Z_a\right) + I_{a2}\left(\frac{Z_A' - Z_B'}{2}\right)\underline{/2\beta} \quad (33)$$

$$V_2 = I_{a1}\left(\frac{Z_A' - Z_B'}{2}\right)\underline{/-2\beta} + I_{a2}\left(\frac{Z_A' + Z_B'}{2} + Z_a\right) \quad (34)$$

Application to Synchronous Machine

In the synchronous machine to which Figure 1a corresponds, phase A represents the field circuit and all damper-bar circuits having their magnetic axes coincident with the pole axis, while phase B represents all circuits having their magnetic axes in the interpolar axis. Equations 33 and 34 are in a form where the direct-axis impedance and the quadrature-axis impedance appear directly. The direct-axis subtransient impedance is

$$Z_d'' = Z_a + Z_A'$$

that is, Z_d'' is the sum of the stator leakage impedance and the impedance which rotor phase A represents (including its magnetizing reactance). Similarly, the quadrature-axis subtransient impedance is

$$Z_q'' = Z_a + Z_B'$$

Equations 33 and 34 now become

$$V_1 = I_{a1}\left(\frac{Z_d'' + Z_q''}{2}\right) + I_{a2}\left(\frac{Z_d'' - Z_q''}{2}\right)\underline{/2\beta} \quad (35)$$

$$V_2\underline{/2\beta} = I_{a1}\left(\frac{Z_d'' - Z_q''}{2}\right) + I_{a2}\left(\frac{Z_d'' + Z_q''}{2}\right)\underline{/2\beta} \quad (36)$$

The subscript a of I_{a1} and I_{a2} need not be carried further. By taking the sum and difference of equations 35 and 36, Z_d'' and Z_q'' are readily obtained:

$$Z_d'' = \frac{V_1 + V_2/2\beta}{I_1 + I_2/2\beta} \quad (37)$$

$$Z_q'' = \frac{V_1 - V_2/2\beta}{I_1 - I_2/2\beta} \quad (38)$$

Z_d'' and Z_q'' are expressed in terms of the symmetrical components of the former action will then be proportional to the cosine of the angle between the pole axis and the magnetic axis of phase a; that is, to the cosine of the angle β. Likewise, the voltage induced in phase b will be proportional to cos $(120-\beta)$ and that in phase c to cos $(120+\beta)$. Therefore

$$V_a = V\cos\beta$$
$$V_b = V\cos(120-\beta)$$
$$V_c = V\cos(120+\beta)$$

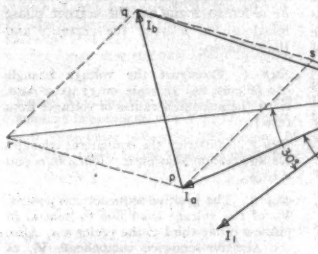

Figure 6a. Graphical solution for sequence components of voltages and currents

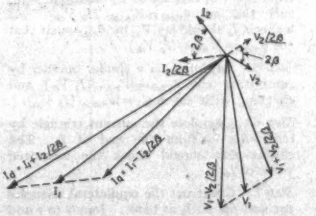

Figure 6b. Graphical procedure for evaluating numerators and denominators of equations 37 and 38

voltage to neutral and of the line current in stator phase a (reference phase) and of the angle by which rotor phase A (that is, the pole axis of a synchronous machine) is displaced forward from the magnetic axis of phase a.

Determination of Angle β

The angle β is the angle by which the axis of rotor phase A (pole axis) is displaced from the magnetic axis of stator phase a. It is considered positive when the displacement is toward the magnetic axis of phase b; that is, in the direction in which the machine would rotate when the sequence of the impressed voltages is abc.

Assume that the field circuit in Figure 3 is excited with alternating current and that the flux distribution along the air gap is essentially sinusoidal and symmetrical about the pole axis. The voltage induced in phase a at standstill by trans-

With a wye connection, the voltages between terminals will be

$$V_{ab} = V_a - V_b = V[\cos\beta - \cos(120-\beta)] = \sqrt{3}V\cos(\beta+30)$$

$$V_{bc} = V_b - V_c = V[\cos(120-\beta) - \cos(120+\beta)] = \sqrt{3}V\sin\beta$$

$$V_{ca} = V_c - V_a = V[\cos(120+\beta) - \cos\beta] = \sqrt{3}V\cos(\beta-30)$$

whence

$$\frac{V_{ab}}{V_{bc}} = \frac{\cos(\beta+30)}{\sin\beta} \quad (39)$$

$$\frac{V_{bc}}{V_{ca}} = \frac{\sin\beta}{\cos(\beta-30)} \quad (40)$$

$$\frac{V_{ca}}{V_{ab}} = \frac{\cos(\beta-30)}{\cos(\beta+30)} \quad (41)$$

These three ratios are plotted with respect to β in Figure 7; and, with the ratios computed from readings of the open-circuit voltages at the terminals, the value of β is readily obtained from the curves. Each ratio yields two values of β, one of which will be common to all three ratios. This common value is the true value of β.

Test Procedure

Test I. The connection diagram for this test is shown in Figure 4. With the field structure blocked in any position whatsoever, three-phase voltages are applied to the stator terminals, these voltages being of such a magnitude that approximately rated current flows in the stator. The sequence of these voltages must be *a–b–c*. If the subtransient impedances of the machine alone are desired, the field terminals should be short-circuited, but if the standstill values of the impedances of the machine as a synchronous motor are desired, the field circuit should be closed through the discharge resistance specified for starting conditions. Measurements are made of the three line-to-line voltages V_{ab}, V_{bc}, and V_{ca}, the three line currents I_a, I_b, and I_c; and four single-phase wattmeter readings designated as $W_{a(ab)}$, $W_{a(ac)}$, $W_{b(bc)}$, and $W_{b(ba)}$, where the first subscript in each case shows the line in which the current coil is connected, and the following pair of subscripts shows the lines between which the potential coil is connected. It is understood, of course, that the polarity of the potential coil with respect to the current coil must be consistent with the order of the subscripts in each case.

Test II. With the rotor in the same position as in test I, a single-phase alternating voltage of rated frequency and of approximately the same magnitude as the rated d-c field voltage is impressed on the field terminals (see Figure 5). The open-circuit terminal voltages V_{ab}, V_{bc}, and V_{ca} are read.

Only one set of readings is necessary in each of the two tests. If a check should be desired, the rotor may be moved to some other position (no particular position being necessary) and a second set of readings taken for both tests I and II.

Calculation Procedure

The vector values (referred to a common reference) of the sequence components of the voltages and currents of test I must be obtained for substitution in equations 37 and 38. Of the several methods available[5,6] one of the most direct is used without proof in the following calculation procedure, in which the diagram for the solution of the currents is superimposed on that for the voltages in order to maintain the correct phase relationships between the currents and the voltages.

Step 1. Construct the voltage triangle *abc* (Figure 6a) to scale on *cb* as a base, using the measured values of voltages from test I.

Step 2. Construct the equilateral triangles *bcn* and *bcm* on *bc* as base. Join *a* to *m* and *a* to *n*.

Step 3. The positive-sequence component, V_1, of the voltage from line to neutral in phase *a* is one-third of the vector *am*. Also, the negative-sequence component, V_2, of the voltage from line to neutral in phase *a* is one-third of the vector *an*.

Step 4. Lay off the current I_a to scale from point *a*, lagging *ab* by an angle $\theta_{a(ab)}$ such that $\cos\theta_{a(ab)} = W_{a(ab)}/(I_a V_{ab})$. As a check, I_a should lag V_{ac} by $\theta_{a(ac)}$ such that $\cos\theta_{a(ac)} = W_{a(ac)}/(I_a V_{ac})$.

Step 5. Lay off I_b in a similar manner by computing $\cos\theta_{b(bc)} = W_{b(bc)}/(I_b V_{bc})$ and checking with $\cos\theta_{b(ba)} = W_{b(ba)}/(I_b V_{ba})$.

Step 6. Complete the current triangle by redrawing I_b from the end of I_a. The closing side should check the measured value of I_c.

Step 7. Construct the equilateral triangles *pqr* and *pqs* on I_b as base. Join *a* to *r* and *a* to *s*.

Step 8. The positive-sequence component, I_1, of the current in line *a* is found by drawing a vector whose length is $1/\sqrt{3}$ times that of *ar* and which is rotated 30° counter clockwise from *ar*. The negative-sequence component, I_2, of the current in line *a* is found by drawing a vector whose length is $1/\sqrt{3}$ times that of *as* and which is rotated 30° clockwise from *as*.

Step 9. Calculate the three ratios V_{ab}/V_{bc}, V_{bc}/V_{ca}, and V_{ca}/V_{ab}, using data from test II.

Step 10. Read angle β from Figure 7. The three ratios will each yield two values of β, but the true value is that which is common to all three cases.

All the necessary information is now available for solving for Z_d'' and Z_q'' from equations 37 and 38. Each of the quantities V_1, V_2, I_1, and I_2 is a vector quantity and must carry its appropriate phase angle with respect to a common reference. The most reasonable common reference is the vector V_1. The magnitude of each vector is scaled from Figure 6a, and also its phase position with respect to the common reference. Equations 37 and 38 may then be solved by the usual procedures of complex algebra.

An alternative graphical procedure for evaluating the numerators and denominators of equations 37 and 38 is outlined in the following additional steps, and is illustrated in Figure 6b, in which the vectors V_1, V_2, I_1, and I_2 have been redrawn from Figure 6a.

Step 11. Rotate V_2 forward through 2β and add it to V_1. The resultant is the numerator of equation 37.

Step 12. Rotate V_2 forward through 2β and subtract it from V_1. The resultant is the numerator of equation 38.

Steps 13 and 14. Proceed as in steps 11 and 12 with the vector I_2. The resultant vectors are the denominators of equations 37 and 38.

It is obvious that Figure 6b may be combined with Figure 6a where the scale is sufficiently large to avoid undue complication.

A complete sample solution, using data from actual tests on a 7,500-kva machine, is shown in Figure 8. It will be observed that V_2 is negligible. This should be so in most cases. V_2 will be appreciable only when the machine under test has a value of Z_q'' widely different from Z_d'', and at the same time the machine being used as a source is relatively small or is feeding in its power through lines of relatively high impedance.

Experimental Verification

Several tests carried out on machines whose characteristics differed widely from one another showed that the values of Z_d'' and Z_q'' as found from equations 37 and 38 agreed satisfactorily with those found from the single-phase test as prescribed in the Test Code for Synchronous Machines. In most cases the corresponding values were within two or three per cent of each other. A second series of tests consisted of taking several sets of readings on each of three machines with the field structures blocked in many different positions in order to verify the

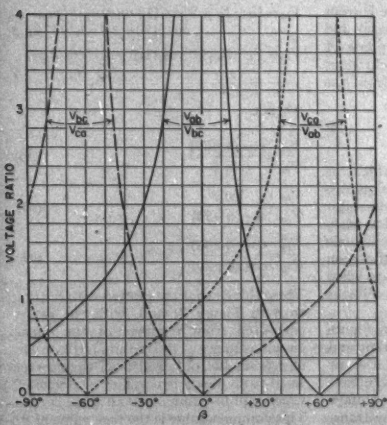

Figure 7. Curves for determining angle β of a wye-connected machine using data of test II

premise of the method that correct values of Z_d'' and Z_q'' can be found with the rotor in any position whatsoever. The results again were satisfactory, the greatest deviation from the mean value being about seven per cent. This corresponds to an error in the per unit value of impedance of about 0.03 on an average machine. In order to check the accuracy with which the angular displacement, β, of the field structure may be found by the use of the curves of Figure 7, a protractor scale was affixed to the end of the shaft in each case so that the displacement could be measured mechanically as

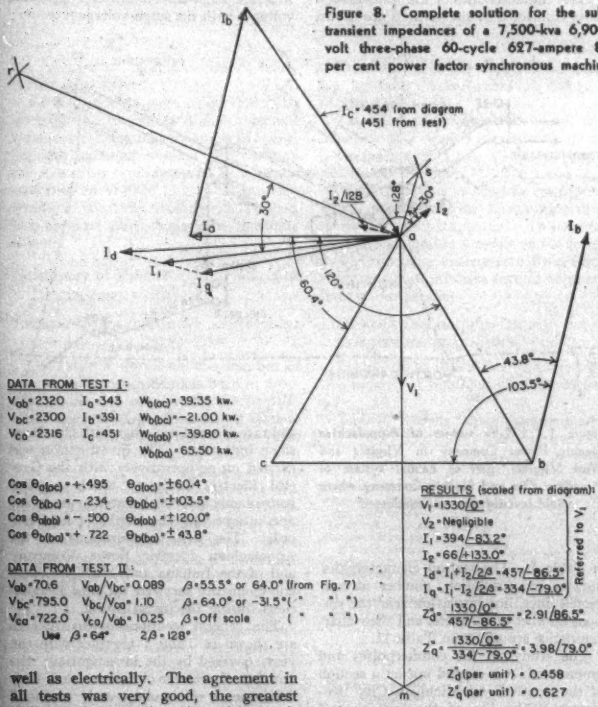

Figure 8. Complete solution for the subtransient impedances of a 7,500-kva 6,900-volt three-phase 60-cycle 627-ampere 80 per cent power factor synchronous machine

DATA FROM TEST I:

V_{ab} = 2320	I_a = 343	$W_{b(bc)}$ = 39.35 kw.
V_{bc} = 2300	I_b = 391	$W_{b(bc)}$ = −21.00 kw.
V_{ca} = 2316	I_c = 451	$W_{a(ab)}$ = −39.80 kw.
		$W_{b(ba)}$ = 65.50 kw.

Cos $\theta_{a(bc)}$ = +.495	$\theta_{a(bc)}$ = ±60.4°
Cos $\theta_{b(bc)}$ = −.234	$\theta_{b(bc)}$ = ±103.5°
Cos $\theta_{a(ab)}$ = −.500	$\theta_{a(ab)}$ = ±120.0°
Cos $\theta_{b(ba)}$ = +.722	$\theta_{b(ba)}$ = ± 43.8°

DATA FROM TEST II:

V_{ab} = 70.6	V_{ab}/V_{bc} = 0.089	β = 55.5° or 64.0° (from Fig. 7)
V_{bc} = 795.0	V_{bc}/V_{ca} = 1.10	β = 64.0° or −31.5° (" " ")
V_{ca} = 722.0	V_{ca}/V_{ab} = 10.25	β = Off scale (" " ")
Use β = 64°		2β = 128°

RESULTS (scaled from diagram):

V_1 = 1330/0°
V_2 = Negligible
I_1 = 394/−83.2°
I_2 = 66/+133.0°
I_d = I_1 + $I_2/2\beta$ = 457/−86.5°
I_q = I_1 − $I_2/2\beta$ = 334/−79.0°
Referred to V_1
Z_d'' = 1330/0° / 457/−86.5° = 2.91/86.5°
Z_q'' = 1330/0° / 334/−79.0° = 3.98/79.0°
Z_d'' (per unit) = 0.458
Z_q'' (per unit) = 0.627

well as electrically. The agreement in all tests was very good, the greatest difference between the values of the angle as found by the two methods being two and one-half electrical degrees.

Appendix I

Magnetomotive Force as a Space Vector

The magnetomotive force due to an alternating current in a concentrated coil on a cylindrical rotor, as in Figure 9, alternates up and down the magnetic axis of the coil, and has a peak height (with respect to time) at all points along the gap of $\sqrt{2}\,NI$, where N is the number of turns and I is the rms current. The fundamental of this "square wave" of magnetomotive force has a peak height, with respect to *time* and *space*, of $(\sqrt{2}\,NI)4/\pi$. For a distributed and short pitch winding the same expression holds provided N includes the breadth and pitch factors.

Using a well-known analysis, the alternating magnetomotive force may be replaced by two traveling space sinusoids, moving in opposite directions around the air gap at synchronous speed, the peak height (in space) of each being $(\sqrt{2}\,NI)2/\pi = 0.9NI$. In a two-pole machine there will be but one space cycle of each component of magnetomotive force. Let the two waves be represented by the vectors $\boldsymbol{M}_f$ and $\boldsymbol{M}_b$ each of which is considered to pass through the positive peak of the wave which it represents. At the instant that the current is zero the net magnetomotive force is zero; and, to represent this condition, the two vectors lie oppositely directed along a line perpendicular to the magnetic axis. At this same instant the conventional vector representing the current in the winding lies along the horizontal reference axis. A moment later, when the current vector has moved forward through α degrees, $\boldsymbol{M}_f$ will also have moved counterclockwise α degrees, and $\boldsymbol{M}_b$ will have moved clockwise

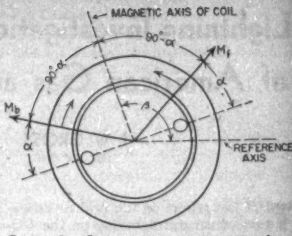

Figure 9. Component magnetomotive-force vectors of a concentrated coil

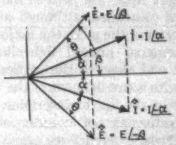

Figure 10. Relations of current and voltage vectors to their conjugates

α degrees, as shown in Figure 9. At this instant the vector expressions for $\boldsymbol{M}_f$ and $\boldsymbol{M}_b$ are

$$\boldsymbol{M}_f = 0.9NI/\beta - 90 + \alpha$$

$$\boldsymbol{M}_b = 0.9\,NI/\beta + 90 - \alpha$$

where β is the angular position of the magnetic axis with respect to an arbitrary reference axis.

By regrouping we obtain

$$\boldsymbol{M}_f = 0.9N(I/\alpha)\,/\beta - 90$$

$$\boldsymbol{M}_b = 0.9N(I/-\alpha)\,/\beta + 90$$

But I/α is the vector expression for the current vector at the instant considered and $I/-\alpha$ is the vector expression for the conjugate of the current vector. Therefore

$$\boldsymbol{M}_f = 0.9N\boldsymbol{I}/\beta - 90 = -j0.9N\boldsymbol{I}/\beta \qquad (42)$$

$$\boldsymbol{M}_b = 0.9N\boldsymbol{\bar{I}}/\beta + 90 = +j0.9N\boldsymbol{\bar{I}}/\beta \qquad (43)$$

Appendix II

Conjugate Vector Relationships

Let the voltage and current in a circuit having an admittance of Y mhos be as shown by the vectors $\boldsymbol{E}$ and $\boldsymbol{I}$ of Figure 10. The current is expressible as

$$\boldsymbol{I} = \boldsymbol{EY}$$

or

$$I/\alpha = (E/\beta)(Y/-\theta) = EY/\beta - \theta$$

But, by definition of conjugates,

$$\boldsymbol{\bar{I}} = I/-\alpha$$

Therefore

$$\boldsymbol{\bar{I}} = EY/-(\beta-\theta) = (E/-\beta)(Y/\theta) = \boldsymbol{\bar{E}Y}$$

This means that the conjugates of current, voltage, and admittance are related by an

Lightning Investigation on 132-Kv System of American Gas and Electric Company

I. W. GROSS
FELLOW AIEE

G. D. LIPPERT
ASSOCIATE AIEE

THE last report on the field investigation of natural lightning on the 132-kv transmission system of the American Gas and Electric Company was presented in a paper by the authors in 1942.[1] Since that time the field research work has been continued, although not as extensively as in the past, the major project being centered around lightning conditions at and close to the stations themselves, with a smaller part of the work being done on the line to determine the relative effectiveness of counterpoises and ground rods.

The objective of this investigation was to determine lightning conditions at major stations where expensive electric equipment is located, the failure of which might have serious effects on equipment, system operation, and electric service. With a better knowledge of the behavior of lightning at stations, it should be possible more adequately to protect important equipment from insulation damage.

The results of the field study from 1942 to, and including part of, 1944 are presented and discussed in this paper. The data have been combined in most cases with that previously obtained, in order to offer a composite picture of all records to date on the particular features studied.

Plan and Scope of Field Work

The major part of the investigation was carried out on a section of the Appalachian Electric Power Company division of the central system of the American Gas and Electric Company which is shown in Figure 1. The isokeraunic levels of the section of country where this part of the system is located range from 40 to 50.

The characteristics of the transmission lines connected to the stations are shown in Table I. The station characteristics such as bus insulation, number of connected lines, line insulation near the station, number of arresters, and their characteristics are shown in Table II.

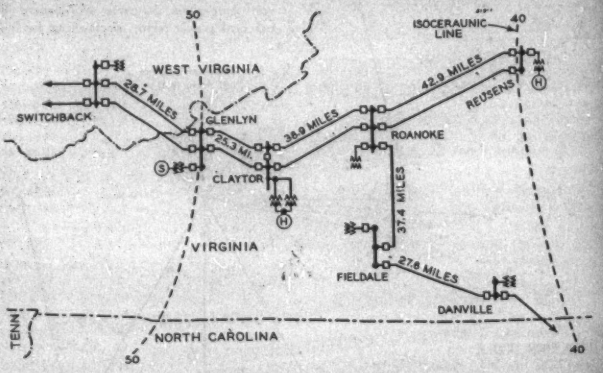

Figure 1. 132-kv system of Appalachian Electric Power Company in Virginia and West Virginia, part of central system of American Gas and Electric Company where field investigation was conducted

The study on the counterpoises and ground rods was carried out on a section of the South Bend–Michigan City two-circuit 132-kv line of the Indiana and Michigan Electric Company in Indiana, which has previously been described.[2]

In planning the field setup instruments were installed to measure currents and voltages as follows:

A. Lightning currents in line conductors, in ground wires, in leads to transformers, and in lightning arresters.

B. Lightning voltages at station busses.

C. Rates of lightning and switching-surge voltage change at stations.

D. Currents in counterpoises, ground rods, and tower footings in one section of a 132-kv line.

All lightning currents were measured with the surge-crest ammeter;[3] lightning voltages with the surge-voltage recorder;[4] and rate of voltage change with the wave-slope indicator.[5] The investigation was carried on co-operatively with the General Electric Company which supplied instruments and collaborated in analyzing and interpreting the results of field records. The field organizations of the Appalachian Electric Power Company and of the Indiana and Michigan Electric Company serviced the field installations during the investigation.

The general locations of instruments are shown in Table I together with the years covered by the investigation; the number of records obtained; and their maximum, minimum, and median* values.

In Table IV is shown the instrument sensitivity or measurement range. The instrument arrangements were designed to cover a range of lightning values which previous experience indicated as most likely to be encountered in the particular circuits in which they were installed. In the case of surge-crest ammeters on line conductors and transformer leads, it was necessary to design the instrument, so as to minimize the demagnetizing effect of 60-cycle fault currents; this resulted in

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I. W. Gross is electrical research engineer and G. D. Lippert is in the engineering department of the American Gas and Electric Service Corporation, New York, N. Y.

expression which is identical in form with that relating the current, voltage, and admittance themselves.

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* The median value is the value which 50 per cent of the records exceed.

Table I. 132-Kv Transmission-Line Characteristics—Appalachian Electric Power Company Division

	Glen Lyn–Switchback	Glen Lyn–Claytor	Claytor–Roanoke	Roanoke–Reusens	Roanoke–Fieldale	Fieldale–Danville
Length of line—miles	28.7	25.3	38.9	42.9	37.4	27.6
Number of towers	128	104	167	200	164	136
Number of circuits	2	2	2	2	1	1
Number of ground wires	1	1	1	1	1	1
Arrangement of conductors	Vertical	Vertical	Vertical	Vertical	Vertical	Vertical
Insulator spacing—inches	5¹/₈	Suspension 4³/₄ Strain 5	Suspension 4³/₄	Circuit 1 4³/₄ & 5 Circuit 2 5¹/₈	5¹/₈	5¹/₈
Number of units—suspension T-M-B	11-11-10	10-10-10	10-10-10	Circuit 1 12-12-10 Circuit 2 10-10-10	10-10-10	10-10-10
Number of units—strain T-M-B	12-12-12	12-12-12	12-12-12	12-12-12	12-12-12	12-12-12
Flashover (kilovolts) of	10(5¹/₈) 930	10(4³/₄) 790	10(4³/₄) 790	10(4³/₄) 790	10(5¹/₈) 930	10(5¹/₈) 930
Insulators—1¹/₂ x 40	11(5¹/₈) 1,010	12(5) 930	12(5) 980	10(5) 840	12(5¹/₈) 1,080	12(5¹/₈) 1,080
Positive wave	12(5¹/₈) 1,080			12(4³/₄) 910 12(5) 980 10(5¹/₈) 930		
Protector tubes	None	Circuit 1 only	Circuit 1 only	None	Yes	Yes
Discharge kilovolts of tubes						
Positive		680	680		680	680
Negative		760	760		760	760

the lower limit of measurements being higher than desired.

All instruments were in service from about May 1 to October 1 each year and were serviced about every two weeks during the lightning season. Instruments for measuring lightning-arrester currents and rate of voltage change at stations were left in service throughout the year but serviced only during the lightning season.

Summary of Records, Analysis, and Discussion

Lightning Disturbances at Stations and Arrester Operations

In Table V is shown the number of years this investigation has been in progress at the five stations on the Appalachian Electric Power Company's system. There has been a total of 21 station years of experience. In this table is also shown the number of times lightning-arrester discharges have been measured at stations. There has been a total of 115 disturbances during this time, or an average of 5.5 lightning disturbances per station per year as indicated by the measurement of lightning currents at the stations. There has been an average of 2.3 times per station per year when lightning arresters discharged. This analysis indicates that on the average one lightning-arrester discharge has occurred for each 2.4 lightning disturbances reaching a station.

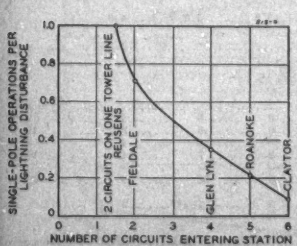


Figure 2. Effect of number of circuits at 132-kv stations on lightning-arrester operations (1939–43 inclusive)

The effect of the number of lines terminating at a station on arrester operation is given in Table V and is shown graphically in Figure 2. The trend of a marked reduction in arrester operations as the number of lines terminating at a station increases is apparent. This checks with theory, and is a result of the lower surge impedance encountered by a surge entering a station where several outgoing lines are in parallel.

Lightning Currents in Line Conductors at Stations

From 1939 to 1943 inclusive, there were 302 records of lightning currents in line conductors at stations, and 130 records of current in single-pole arresters. These data are all shown as magnitude–frequency curves in Figure 3. These magnitude–frequency curves show not only a summary of all conductor and lightning-arrester currents at the five stations, but also the currents at each separate station. The maximum line-conductor current obtained at a station was 11,500 amperes. Ten per cent of the currents were 3,500 amperes or greater, and 50 per cent of the currents were at least 2,000 amperes.

Currents Into and Out of Stations

Of the 302 lightning currents in conductors at stations, 143 were flowing toward the station and 159 were flowing away from the station.

Table II. 132-Kv Station Characteristics—Appalachian Electric Power Company Division

Station	Glen Lyn	Claytor	Roanoke	Reusens	Fieldale
Number of suspension insulator units on station bus	12	12	12	12	12
Flashover kilovolts of bus insulators	980–1,080	980	910–980	910–980	1,080
Number of connected circuits	4	6**	5	2	2
Reduced line insulation at station entrance	All except Claytor number 1 which is tube-equipped	Roanoke number 2 and Glen Lyn number 2—Roanoke number 1 and Glen Lyn number 1 are tube-equipped	All except Claytor number 1 and Fieldale which are tube-equipped	Yes	No—tube-equipped
Number of towers in reduced section	5	5	5	5	
Number of suspension and strain insulators in reduced section	9	9	9	9	
Flashover kilovolts of reduced section (1¹/₂x40 positive wave)	720–850	720–765	720–850	720–850	
Number of 3-pole lightning arresters	4	4	3	3	
Kilovolt maximum 60-cycle rating	106	109	106-109-121	106–109	109
Arrester-gap breakdown*	635	388	635-388-430	635–388	388
IR at 5,000 amperes*	353	363	353-363-408	353–363	362

* Average industry values.

** Including two circuits of 1,000 feet.

Table III. Lightning-Measuring Instruments, Locations, and Number and Magnitude of Records Obtained on 132-Kv System

Reference	Instrument Location	Instrument Years	Years of Operation	Number of Records	Record Magnitude Maximum	Median	Minimum**
1.	Tower legs above ground	456	1939–44	123	15,100	2,400	1,000
2.	Tower legs below ground	378	1939–44	66	6,800	1,650	1,000
3.	250-foot counterpoises	126	1939–44	55	11,000	2,700	200
4.	Ground rods at towers	393	1939–44	121	20,000	1,200	200
5.	Ground wires at towers near stations	136	1940–43	41	36,000	2,400	1,000
6.	Ground wires at stations*	100	1940–43	60	10,300	1,700	1,000
7.	Conductors at towers near stations	228	1941–42	171	14,600	2,200	1,000
8.	Conductors at stations	210	1939–43	302	11,500	2,000	1,000
9.	Conductors at transformers	23	1944	0			
10.	Wave-scope indicators at stations	115	1939–9/1/44	1,035	810	115	10
11.	Arresters at stations	288†	1936–43	261‡	4,100	500	200
12.	Voltage recorders at stations	33	1939–43	429	525	165	100

*Where three ground wires are in parallel.
**Lower limit of link registration—trace records.
†Single-pole years.
‡Single-pole records.

Table IV. Instrument Measurement Range

Surge-crest ammeters	
On tower legs	1,600 to 55,000 amperes
On ground wires	1,000 to 72,000 amperes
On line conductors	1,000 to 55,000 amperes
On lightning arresters	200 to 14,400 amperes
On ground rods	200 to 24,000 amperes
On counterpoises	200 to 24,000 amperes
Wave-slope indicator	10 to 10,000 kv per microsecond
Surge-voltage recorder	100 to 1,300 kv

Table VI. Simultaneous Line-Conductor Currents Into and Out of Stations With Accompanying Arrester Currents

24 Selected Records (3,000 Amperes or Greater—Either Incoming or Outgoing)

Station	Total Current Into Station, Amperes	Total Current Out of Station, Amperes	Arrester Current, Amperes	Arrester Poles Discharging
Glen Lyn	11,300	8,700	N*	
Glen Lyn	7,500	1,000	N	
Glen Lyn	5,000	1,000	N	
Glen Lyn	2,800	3,000	N	
Glen Lyn	3,400	2,400	300	1
Glen Lyn	2,300	3,400	N	
Claytor	3,000	1,000	N	
Claytor	2,000	3,300	N	
Claytor	2,000	3,800	N	
Claytor	2,400	3,400	N	
Claytor	3,700	2,700	N	
Claytor	3,000	2,000	N	
Claytor	1,000	4,200	N	
Claytor	5,000	1,000	N	
Claytor	8,200	1,000	850	2
Claytor	1,000	4,000	1,750	2
Claytor	4,600	3,000	N	
Roanoke	1,000	5,300	1,750	2
Roanoke	2,000	3,300	350	1
Roanoke	1,000	3,000	200	1
Roanoke	3,000	2,000	450	1
Roanoke	3,000	2,000	N	
Roanoke	4,800	8,000	N	
Roanoke	2,000	5,800	N	

* N indicates no record obtained.

In Table VI are shown simultaneously obtained currents flowing toward and away from stations and the accompanying station arrester current, all three recorded on the same phase wire. In each case the current values given are the summation of all currents measured in line wires and arresters. Of the 58 cases showing simultaneous line currents into and out of the station, 24 of the highest records were selected for analysis in Table VI. From the table it appears that there is no characteristic trend between the magnitudes of currents entering and leaving a station, nor between these currents and the arrester current. However, as there were other station current paths where no instruments were installed and as the instrument sensitivity does not permit measurement of low values of current, the comparison of currents by the above method may not be significant. The question may well arise as to why lightning arresters in some cases show no discharge current with currents in line conductors of 3,000 amperes or more. A line current of 3,000 amperes and line surge impedance of 400 ohms would produce a line voltage of 1,200 kv, which should cause arrester operation. The explanation may be that recorded line currents are the addition of several lightning surges—not merely one. Again, the current measured may be the result of reflection at a transition point where the surge impedance becomes lower and the line voltage at the station likewise lower.

Current Attenuation and Reflection Adjacent to Stations

During 1941 and 1942 surge-crest ammeters were in service on line conductors at the five stations and on all circuits at intervals of approximately one-half mile and one mile distant from the station. By this arrangement it was planned to obtain data on attenuation and reflection of lightning currents in line conductors. Of the 58 records obtained, 23 were of low magnitude or of inconsistent direction of current flow and were rejected in the tabulation. In Table VII are shown the 35 records selected for analysis. The averages of currents flowing toward the station were 2,800 amperes, 2,600 amperes, and 2,810 amperes, respectively, at the station, one-half mile out, and one mile out. Individual cases, however, varied considerably from the average results, and the data do not indicate any definite trend. If the currents attenuated to any extent, the results are obscured by possible reflection at the station where a change of surge impedance is encountered.

In the case of currents flowing away from a station it was believed that, if appreciable attentuation took place, it would not be obscured by reflection from the station. An average of all the records indicated currents at the station of

Table V. Lightning Disturbances at 132-Kv Stations, 1939–43 Inclusive

	Roanoke	Glen Lyn	Claytor	Reusens	Fieldale	Totals
Station years of investigation	5	4	4	4	4	21 station years
All lightning disturbances*						
1939	4					4
1940	8	6	7	3	4	28
1941	6	6	5	5	3	25
1942	8	3	4	5	5	25
1943	9	5	7	7	5	33
Total	35	20	23	20	17	115
Average disturbance per year	7.0	5.0	5.8	5.0	4.3	
Disturbance per station per year—1939–43 inclusive						
Experience years (1939–43 inclusive)						21
Disturbances						115
Disturbances per station per year						5.5
Lightning arrester discharges						
1939	2					2
1940	3	2	0	3	1	9
1941	1	3	0	5	3	12
1942	0	1	0	5	4	10
1943	2	1	2	7	4	16
Total	8	7	2	20	12	49
Number of lines entering station	5	4	6	1½**	2	
Lightning-arrester operations per lightning disturbance	0.228	0.350	0.087	1.00	0.710	0.425 avg
Average discharges per station per year						49/21 = 2.3

* Indicated by measurement of lightning current in conductors and/or arresters.
** Based on two circuits entering station on same towers.

2,670 amperes; at one-half mile out of 2,520 amperes; and one mile out of 2,450 amperes. Although the average values indicated a slight attenuation, individual cases vary considerably from the average, and there appears to be no pronounced trend.

There were eight instances where currents of 2,000 amperes or more were measured at the station entrance, one-half mile out, and one mile out, in which the direction of current flow at one of these points was reversed with respect to that at the other two. A tabulation of these cases is shown in Table VIII. The explanation for this may be that either a lighting stroke or a line flashover occurred between measurement points. This seems to indicate that some strokes and line flashovers have occurred within a mile of the stations without causing any arrester operation or damage to station apparatus.

Figure 3. Lightning currents in conductors and arresters at 132-kv stations (1939–43 inclusive)

I—Arrester currents
II—Conductor currents
A—Roanoke station—126 conductor records, 23 arrester records
B—Fieldale station—24 conductor records, 26 arrester records
C—Reusens station—10 conductor records, 66 arrester records
D—Claytor station—76 conductor records, 6 arrester records
E—Glen Lyn station—66 conductor records, 9 arrester records
F—All records—302 conductor records, 130 arrester records

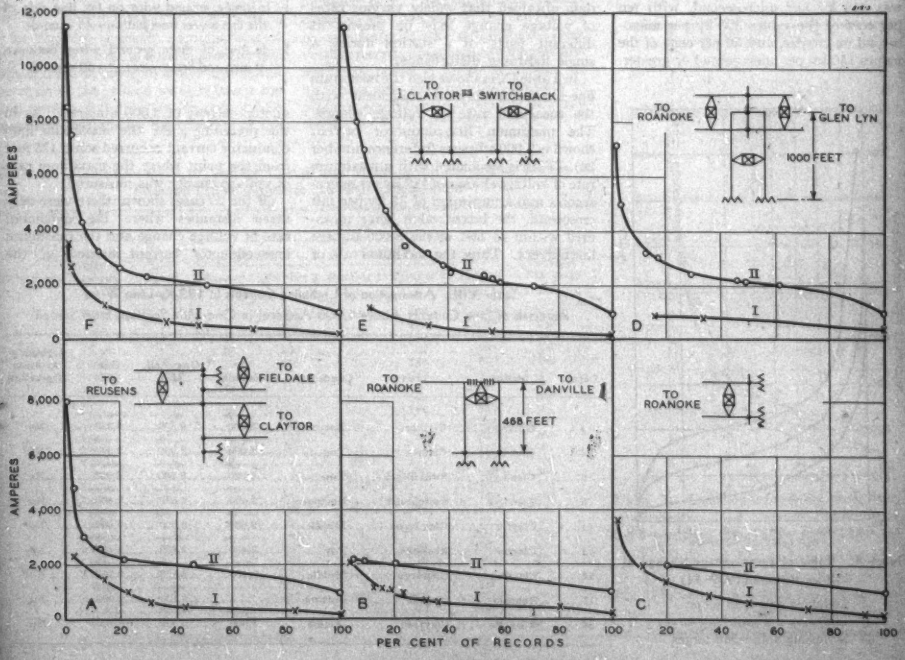
Lightning-Arrester Currents at 132-Kv Stations

Measurements were obtained of currents in lightning arresters at the five stations from 1936 to 1944 inclusive. The maximum current obtained during this period was 4,100 amperes. This record, however, was obtained at a time when no other instruments were in service at the station, and therefore no correlation with other lightning data was possible.

The arrester records shown in Figure 3 (1940–43 inclusive) include only those obtained when instruments were in service to measure line-conductor currents. However, the inclusion of data obtained from 1936 to 1939 inclusive on arresters only does not alter the shape of the magnitude-frequency curve, except to increase the maximum value of current to 4,100 amperes. Of the lightning-arrester records obtained simultaneously with line-conductor currents, ten per cent were 1,500 amperes or higher, and 50 per cent were 500 amperes or higher. Although the maximum value of arrester current measured in this investigation was only 4,100 amperes, on another part of the system a maximum arrester current of

Table VII. Attenuation of Lightning Currents in 132-Kv-Line Wires Near Stations (1941–1942)

Currents (Amperes) Flowing					
Toward Station			From Station		
At Station	½ Mile Out	1 Mile Out	At Station	½ Mile Out	1 Mile Out
2,400	2,400	2,500	2,800	1,000	2,400
3,400	3,900	3,800	2,700	2,800	3,000
1,000	1,000	2,000	3,500	7,400	3,800
2,300	2,700	2,700	2,900	2,200	2,000
3,000	2,800	3,500	3,200	3,100	3,600
8,500	5,300	7,300	3,400	4,400	3,400
3,200	2,300	3,000	2,000	3,000	2,300
2,300	2,000	1,000	3,200	2,400	2,800
2,700	2,600	3,200	2,900	3,400	2,400
1,000	2,000	2,000	2,100	1,000	2,000
2,000	2,000	1,000	1,000	1,000	2,000
1,000	1,000	2,000	1,000	1,000	3,000
5,000	3,700	3,600	2,100	2,800	2,800
1,000	2,300	2,300	2,000	2,600	2,100
3,200	2,900	3,200	1,600	2,100	1,000
			2,600	2,400	2,400
			2,000	2,000	2,400
			2,700	2,000	3,400
			2,200	2,000	2,400
			2,000	2,000	1,000
Average					
2,800	2,600	2,810	2,670	2,520	2,450



16,000 amperes was measured in an arrester on the 132-kv system—the result of a stroke within 400 feet of the station.

Rates of Voltage Change at Stations

In a previous paper[1] the authors presented data on the rate of surge-voltage change at stations comprising 539 wave-slope indicator records for 1939 to 1941 inclusive. In the past three years there have been obtained 486 additional wave-slope-indicator records making a total of 1,025. These six years' records have been analyzed and the results are presented here.

Of the 1,025 records, 353 were rejected because they did not lend themselves readily to accurate analysis. The 672 records selected for analysis have been segregated into three groups. The first group consists of 348 surges believed to be attributable to switching only; the second group, 291 records which were the result of lighting and switching; and the third group of 33 surges interpreted as resulting from lightning only. These three groups of records are shown as magnitude-frequency curves in Figure 4. The maximum rate of voltage change caused by lightning only was 810 kv per microsecond, with ten per cent of the records 475 kv per microsecond or greater, and 50 per cent of the records 220 kv per microsecond or greater. In the lightning and switching group, the maximum value was 648 kv per microsecond, with ten per cent of the values 300 kv per microsecond or greater, and 50 per cent of the values 150 kv per microsecond or greater.

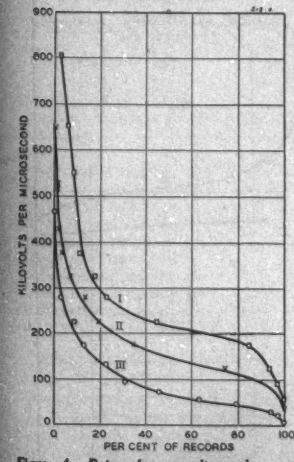


Figure 4. Rates of surge-voltage change at 132-kv stations (1939–44)

I—Lightning only—33 surges
II—Lightning and switching surges
III—Switching only—348 surges

In the switching group, the rates of voltage change were a maximum of 470 kv per microsecond, ten per cent being 200 kv per microsecond or greater and 50 per cent being 115 kv per microsecond or greater.

At the Roanoke 132-kv substation, wave-slope indicators were installed on phases one and three of all connected lines. The wave-slope indicators were located on carrier-current capacitors which are connected to the incoming line ahead of all other station apparatus and are some 70 circuit feet from the station bus. The maximum distance between measuring locations was approximately 280 circuit feet. In Table IX are shown 25 simultaneously obtained records of the rate of voltage change at different locations in the station.

From the data it is seen that the rate of voltage change due to a surge may vary widely between different points in the same station. An extreme case is shown in reference 14 of Table IX. Here a rate of voltage change of 470 kv per microsecond was recorded at the line entrance of Reusens number 2, whereas at the line entrance of Reusens number 1, some 200 circuit feet distant, the rate of voltage change was below the minimum sensitivity of the wave-slope indicator (ten kilovolts per microsecond). Numerous similar occurrences are shown in this same table. Thus it appears from the data obtained that widely varying rates of voltage change may be present at different parts of a station during a single lightning disturbance.

In Table IX is shown also the maximum line-conductor currents coincident with the measured rate of voltage change. The maximum line-conductor current shown is 8,000 amperes (reference number 24). This is associated with a maximum rate of voltage change of 412 kv per microsecond and a minimum of 33 kv per microsecond, the latter value being measured within 25 feet of the 8,000-ampere line current. Thus, the maximum rate of voltage change in this case was recorded at some distance (250 feet approximately) from where the maximum line-conductor current was measured. In reference number 14 of this same table, the rate of voltage change of 470 kv per microsecond was measured adjacent to a line-conductor current of 2,000 amperes. As in the preceding case, the maximum line-conductor current occurred some 175 feet from the point where the maximum rate of voltage change was measured.

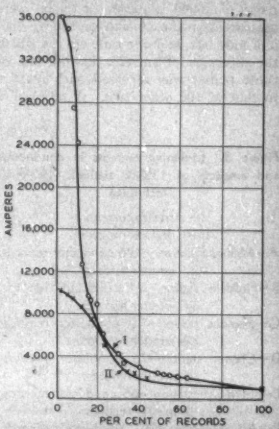


Figure 5. Lightning currents in overhead ground wires at 132-kv stations

I—In single ground wire on the line side of the first tower from station—41 records

II—In one of three ground wires between station and first tower out—60 records

Of the 25 cases shown, there were only three instances where the maximum rate of voltage change and the maximum line-conductor current existed at the

Table VIII. Attenuation of Lightning Currents in 132-Kv-Line Wires

Reversals of Line Currents Above 1,000 Amperes in One-Mile Sections From Station

Case	Station	Line	Conductor	Station	One-Half Mile	One Mile	Lightning-Arrester Operation
				→	←	←	
4	Glen Lyn	Claytor	Bottom	3,600	9,300	9,300	No
				←	→	→	
4	Glen Lyn	Claytor	Top	5,000	3,900	3,300	No
				→	←	←	
6	Glen Lyn	Switchback	Top	2,000	2,200	8,100	No
				→	←	←	
6	Glen Lyn	Switchback	Bottom	2,400	2,800	2,400	No
				→	→	←	
11	Claytor	Glen Lyn	Middle	2,000	2,000	2,000	No
				→	←	→	
13	Claytor	Roanoke	Top	2,400	2,800	2,400	No
				←	→	→	
14	Claytor	Glen Lyn	Middle	3,400	2,800	2,300	No
					←	→	
17	Roanoke	Claytor	Bottom		2,100	2,000	No
				→	←	←	
24	Roanoke	Claytor	Middle	1,000	2,500	2,700	No

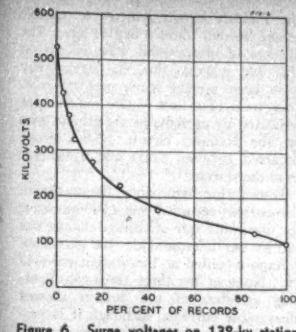


Figure 6. Surge voltages on 132-kv station buses (1940–43 inclusive)

same point. If it be assumed that the maximum line-conductor currents are records obtained nearest to the lightning stroke initiating the disturbance, it would appear that the highest rates of voltage change are not caused by the initiating surge but by other conditions within the station, possibly voltage reflections from apparatus terminals, and similar causes. If this be true, it dictates the necessity of placing protective devices close to the apparatus to be protected.

Ground-Wire Currents at Stations

In Figure 5 is shown a comparison of ground-wire currents obtained on the line side of the first tower from the station and currents in the ground wires between the first tower and the station structure. The maximum current on the line side of the first tower was 36,000 amperes, and the maximum in any one of the three parallel ground wires adjacent to the station structure was 10,300. In general, the current divided equally between the three parallel ground wires, although there were some exceptions to this at lower values of current. Although the two curves in Figures 5 do not have the same general shape, it is believed that this is not particularly significant.

The ground-wire current distribution at the first tower out from a station for the three different ground-wire arrangements investigated is shown in Table X. Though it might be expected that the sum of currents in multiple-ground wires between station and the first tower out nearly would equal the ground-wire current on the line side of the tower, this is not always true. The reason, no doubt, is that no account has been taken of the unmeasured tower current itself.

Lightning Voltages at 132-Kv Stations

A total of 429 bus-voltage records were obtained during 1940 to 1943 inclusive from surge-voltage recorders. These were in service at the Roanoke, Fieldale, and Claytor stations during 1940 and 1941, and at the Roanoke station only during 1942, 1943, and 1944. As records of appreciable magnitude were not obtained during 1944, they have not been included here. The maximum voltage obtained was 525 kv, 50 per cent of the records being 165 kv or greater. These voltage records are shown as a magnitude–frequency curve in Figure 6. These are all below the safe impulse strength of modern equipment used on 132-kv systems.

Table IX. Coincident Rates of Voltage Change and Maximum Lightning Line Currents at Roanoke 132-Kv Substation (1940–1943 Inclusive)

Reference	Maximum Line Amperes	Phase	Kv/μs Claytor Number 1	Claytor Number 2	Reusens Number 1	Reusens Number 2	Fieldale	Lightning-Arrester Discharge
1	2,500	1		115	64	168	102*	No
2	2,000	1		126		212	136*	Yes
3	2,200	3	94		172	155	150*	Yes—2
4	2,400	1	27	300		52	80*	No
5	2,000	1		230	72	186	55*	Yes
6	2,400	1		40	10	72	92*	Yes
7	2,800	3	164	110	116		45*	No
8	2,000	1			168	288	97*	No
9	2,000	1	17	270	228*	108	76*	No
10	3,200	3		42	24		67*	No
11	2,000	1		320		80	64*	No
12	2,600	3	44	37	156		13*	No
13	2,900	3	132		24		53*	No
14	2,000	1				470	82*	No
15	2,000	3			235*		245	No
16	2,000	1		155		64	71*	No
17	2,200	1	*	332	95	245		No
18	2,000	1		150			*	No
19	2,000	1		145	*		210	Yes
20	3,700	1		380	*	64	310	No
21	2,000	3		35	80*	10	146	No
22	3,800	1		120		212*		No
23	3,000	1		290	*		178	No
24	8,000	1		412	33*	216	133	No
25	2,000	1		36		64	179*	No

* Circuit on which maximum current was measured.

Lightning Currents in Transformer Leads

During the 1944 lightning season, instruments were in service on all three leads of seven 132-kv transformer banks to measure lightning currents to the transformers. No records have been obtained from these instruments this year.

Ground Rod, Counterpoise, and Tower-Footing Currents

Surge-crest ammeters were installed on the South Bend–Michigan City 132-kv line to obtain a complete record of current flowing in counterpoises, ground rods, and tower legs in order to determine which of these members was most effective in carrying lightning currents.

Magnitude–frequency curves of all currents measured in tower legs, counterpoises, and ground rods are shown in Figure 7.

A total of 29 cases was obtained during 1939 to 1944 inclusive, where currents were measured in two or more members. In Table XI are shown ten cases where a comparison is made between simultaneously obtained measurements in three members—tower footings, ground rods, and counterpoises. In all cases except one (case 10), the tower footing was most effective in carrying lightning current, based on d-c conductances. The average of the ten cases indicates the counter-

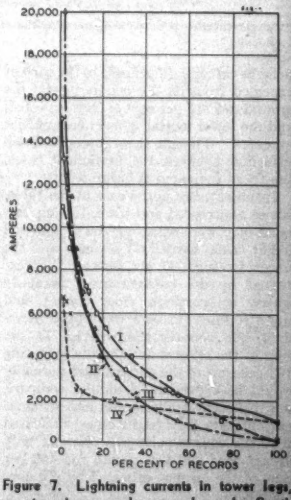


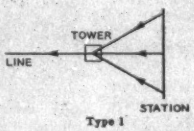
Figure 7. Lightning currents in tower legs, counterpoises, and ground rods—South Bend–Michigan City 132-kv line (1939–44)

I—52 currents in 250-foot counterpoises
II—115 currents in tower legs above ground
III—111 currents in ground rods (10 to 120 feet)
IV—65 currents in tower legs below ground

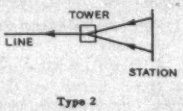
Table X. Lightning Current in Ground Wires at 132-Kv Stations, 1940–1944

(Only Records Where 3,000 Amperes or Above Were Measured in at Least One Wire)

Type 1. Glen Lyn, Claytor, Roanoke			Type 2. Reusens			Type 3. Fieldale		
Amperes*.								
Line Side	Station Side	Total Station Side	Line Side	Station Side	Total Station Side	Line Side	Station	Line Side
−2,500	2,000		17,200	10,000		−1,000	−4,300	−1,000
	1,000	6,000		5,800	15,800			
	3,000					1,000	−11,700	
36,000	8,400		12,200	12,500		−2,400	5,800	21,000
	10,300	27,700		33,000	45,500			
	9,000							
9,500	1,000		3,000				3,000	2,000
	1,000	3,000				−4,000	20,600	20,100
	1,000			4,100				
4,500	9,700			3,500	7,600		2,900	3,400
	4,800	23,800	5,000	2,000	2,000	−4,800		
	9,500							
−9,400	−2,000					2,900	3,400	−1,000
	−2,400	−4,400				2,900	7,100	12,000
36,000	8,500							
	7,400	24,200						
	8,300							
24,300	5,000							
	6,000	18,300						
	7,300							
6,000	1,000							
	1,000	4,100						
	2,100							
12,700	4,600							
	3,300	11,200						
	3,300							
4,200								
−3,000	−1,000							
		−2,000						
	−1,000							
27,300	8,500							
	7,000	25,750						
	10,250							
3,400								
9,750	2,400							
	1,000	5,400						
	2,000							



Type 1



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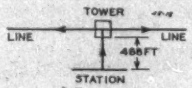

Type 3

* Current direction as shown in figure, otherwise shown (−).

poise as carrying 70 per cent of the current expected from its d-c conductances, the ground rod 115 per cent of that expected, and the tower footing 302 per cent of that expected. Though there is considerable variation between the individual cases, the trend indicated is quite definite.

In other cases not shown in the table, where ground-rod and tower-footing currents only were recorded, the ground rod (eight cases) carried 83 per cent and the tower footing 180 per cent of that expected by d-c conductance. Similarly where counterpoise (four cases) and tower-footing currents only were measured, the counterpoises carried 71 per cent of the current and the tower footing 393 per cent of the current that normally would be expected. A similar comparison between counterpoise and ground-rod currents only (eight cases) indicated that the counterpoise was carrying only 81 per cent and the ground rod 162 per cent of the current expected by d-c conductance.

Summarizing the data presented here, the tower footing is most effective in carrying lightning current; the ground rods less effective; and the counterpoise least effective. In this location the efficiency of ten-foot ground rods is very low. The maximum ground-rod efficiency is shown for ground rods of 40 to 60 feet in length. The type of soil was sandy loam of moderately high resistivity; the ground rods ranged from 10 to 120 feet in length; and the counterpoises were 2/0 copper 250 feet long, buried 18 inches. Tower footings were of the grillage type about five feet square and ten feet deep.

Discussion of Special Records

In studying a large quantity of summarized data such as has been obtained during this investigation, an analysis of a typical case may be of interest. In Figure 8 are shown typical records of a lightning disturbance at the Roanoke 132-kv station. During the servicing period of approximately two weeks, two lightning storms were reported in the general vicinity of the station. From a study of the lightning currents recorded (Figure 8), it appears that there were five lightning strokes to the 132-kv system in the general vicinity of the station. Three of these strokes were on the Claytor circuit: one between the first and fifth towers of 26,000 amperes or more; one between the fifth and seventh towers of possibly 36,000 amperes; and one stroke beyond the seventh tower of 42,000 amperes or higher. Conductor currents measured in the Fieldale circuit indicate a possible stroke beyond tower 8 of this line. The absence of any ground wire records on this line suggests that the stroke may have been several spans past tower 8. One stroke of at least 65,000 amperes was indicated by currents in the ground wire on the Reusens circuit. This stroke occurred between 3,500 and 9,300 feet from the station.

During this disturbance, the maximum line current recorded was 2,700 amperes; the maximum rate of voltage change was 440 kv per microsecond; the maximum voltage recorded at the station was 413 kv. None of the three three-pole lightning arresters at the station showed measurable currents, although it is possible that the arresters operated but the current was below the measurement range of the instruments.

In view of the records obtained in this one case the following statements seem justified:

1. Where lightning strokes occur some 1,500 feet or more from a station, if the line conductors are shielded, maximum lightning currents in the line wires at the station are in the order of 2,700 amperes or less.

2. Under the same conditions the incoming lightning voltages are not sufficient to cause arrester operation in the station.

3. Rates of voltage change at the station resulting from these nearby surges ranged as high as 440 kv per microsecond, although the nearest stroke was probably 1,500 feet distant. This feature may be significant in indicating that higher rates of voltage change at the station may occur, if the strokes are nearer the station.

Summary and Conclusions

From the results of this investigation, the summary data of which have been presented above, the following conclusions are drawn:

1. Lightning disturbances at five stations over a four-year period averaged 5.5 per station per year. Of these, 2.3 per station per year were of sufficient magnitude to cause arrester operation.

2. Lightning currents in conductors at stations showed a median value of 2,000 amperes. Seven per cent were 4,000 amperes or above and the highest was 11,500 amperes. All lines were shielded with overhead ground wires terminating on the station structure.

3. There appears to be no appreciable attenuation of lightning currents in line conductors within the first mile of the station.

4. The highest lightning-arrester current measured was 4,100 amperes, although elsewhere on the 132-kv system one current of 16,000 amperes was recorded.

Based on these results and similar records of arrester current obtained by the authors and others, it appears that the AIEE Standards for distribution and station-type arresters of 65,000- and 100,000-ampere lightning-current discharges are consider-

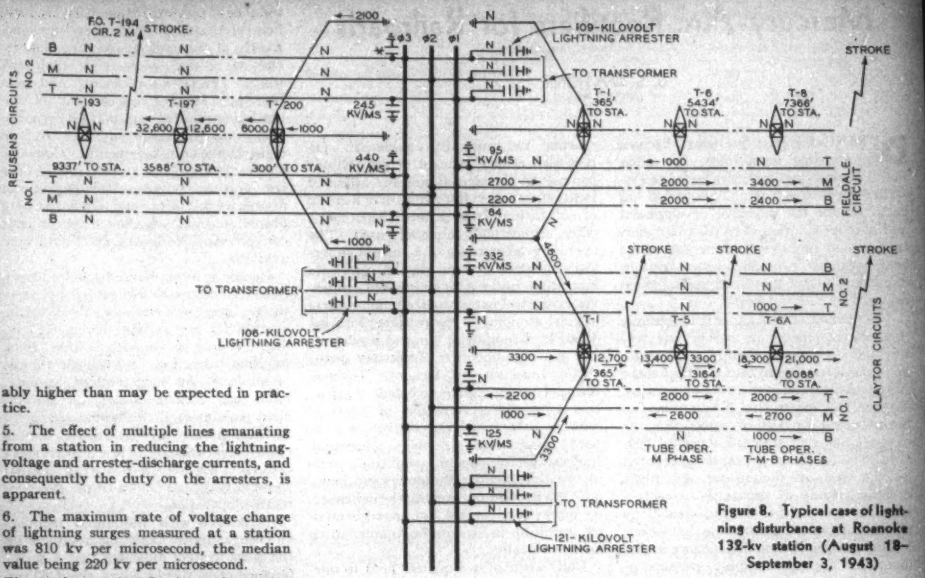

Figure 8. Typical case of lightning disturbance at Roanoke 132-kv station (August 18–September 3, 1943)

ably higher than may be expected in practice.

5. The effect of multiple lines emanating from a station in reducing the lightning-voltage and arrester-discharge currents, and consequently the duty on the arresters, is apparent.

6. The maximum rate of voltage change of lightning surges measured at a station was 810 kv per microsecond, the median value being 220 kv per microsecond.

The maximum rate of voltage change due to switching surges was 470 kv per microsecond and the median value was 115 kv per microsecond. When allowances are made for a reasonable factor of safety, the present generally accepted 1,000 kv per microsecond rate of rise for test specifications on apparatus seems reasonable.

7. The rates of voltage change measured within a station varied considerably at different points. Rates of change as high as 470 kv per microsecond were observed at one point in the station, whereas the rate of voltage change at other points was below the range of measurement (ten kilovolts per microsecond). This indicates clearly the necessity of keeping protective devices close to the equipment to be protected.

8. No consistent ratio was observed between lightning currents in conductors and the rates of voltage change at station entrances.

9. The maximum lightning voltage measured at any substation was 525 kv with 50 per cent of the records 465 kv or greater. This maximum voltage value is well below the safe insulation strength of modern 132-kv station equipment and within the range expected from the arrester protection.

10. In this investigation no consistent relationship was found between lightning currents and voltages at a station.

Lightning currents in line conductors of 11,500, 8,500, 8,000, 7,500, and 6,500 amperes were recorded without any arrester operations recorded. These were accompanied by measured maximum rates of voltage rise of 100 to 160 kv per microsecond. The arresters at the station where these high-current records were obtained have a gap breakdown of 635 kv. In other instances arresters discharged where the

Table XI. Division of Lightning Current Between Counterpoises, Ground Rods, and Tower Footings, South Bend–Michigan City 132-Kv Line

Case 1	Member 2	Length, Feet 3	Resistance, Ohms 4	Measured Amperes 5	Per Cent Conductivity 6	Per Cent Current 7	Relative Efficiency Ratio 7/6 8
1	Counterpoise	250	15	7,800	82.3	64.5	0.78
	Ground rod	60	110	2,500	11.4	20.5	1.80
	Tower footing	10	200	1,800	6.3	15.0	2.37
2	Counterpoise	250	14	3,300	69.5	51.0	0.73
	Ground rod	10	100	200	9.8	3.0	0.31
	Tower footing	10	48	3,000	20.7	46.0	2.23
3	Counterpoise	250	10	5,100	61.0	43.5	0.72
	Ground rod	40	25	3,300	26.2	28.3	1.08
	Tower footing	10	48	3,300	12.8	28.2	2.20
4	Counterpoise	250	14	3,300	63.7	50.7	0.80
	Ground rod	10	45	200	19.5	3.1	0.16
	Tower footing	10	48	3,000	16.8	46.2	2.75
5	Counterpoise	250	9	3,000	71.8	52.2	0.73
	Ground rod	100	32	1,250	20.2	21.7	1.07
	Tower footing	10	80	1,500	8.0	26.1	3.14
6	Counterpoise	250	8	9,000	75.2	42.5	0.55
	Ground rod	49	32	5,400	18.8	25.5	1.36
	Tower footing	10	100	6,800	6.0	32.0	5.34
7	Counterpoise	250	14	6,300	67.6	66.3	0.99
	Ground rod	32	48	200	26.5	2.1	0.08
	Tower footing	10	160	3,000	5.9	31.6	5.35
8	Counterpoise	250	10	5,100	69.4	44.8	0.65
	Ground rod	40	40	3,300	17.4	29.0	1.67
	Tower footing	10	48	3,000	13.2	26.2	1.98
9	Counterpoise	250	9	4,600	71.8	61.4	0.85
	Ground rod	100	32	1,400	20.2	18.7	0.92
	Tower footing	10	80	1,500	8.0	20.0	2.50
10	Counterpoise	250	10	800	71.2	13.7	0.192
	Ground rod	65	36	3,550	19.8	60.7	3.06
	Tower footing	10	80	1,500	9.0	25.6	2.84
Average values							
	Counterpoise						0.70
	Ground rod						1.15
	Tower footing						3.02

Mercury-Arc Rectifiers for Railroads

S. S. WATKINS
MEMBER AIEE

DURING the past five years, because of wartime restrictions, few additional mercury-arc rectifiers have been installed for railroad use. This period has been notable for intensive development and mass production of rectifiers for electrochemical industries where they have been operated to produce concentrations of current output greatly exceeding those required by railroad loads.

The purpose of this paper is to examine those developments in mercury-arc rectifiers and associated equipment that deserve consideration in future plans for the supply of direct current for moving trains. To this end, experience of operators has been studied for data of value. Results of space and cost studies for typical 700-volt substations are presented, prepared on the basis of present-day apparatus designs. Study of apparatus characteristics is not limited to the conditions chosen for typical substations but is extended to include their significance in the design of d-c power-supply systems in general.

Operation, Control, and Maintenance

The majority of mercury-arc rectifier substations for transit and railroad service are nonattended with automatic starting and protective equipment. Direct-wire remote control or supervisory control[1] to the nearest suitably attended location, or supervisory control of a group of substations from a load dispatcher's office, are methods commonly used. The operating advantages of a central supervisory-control system should cause its increasing use. As a minimum, supervisory control must provide remote starting and stopping of the rectifier, with indication of running or stopped condition, and remote indication of rectifier automatic shutdown and lockout. Telemetering of output often is included. Indication of running condition of control-battery charger or telemetering of battery voltage often is used. Abnormal temperature or vacuum conditions such as to cause rectifier shutdown and lockout[2] usually are not separately indicated by supervisory control, but are registered on operation indicators or annunciators in the substation.

Daily visits of one-quarter hour to one hour to each substation are the practice of several organizations maintaining a large number of unattended mercury-arc rectifiers of the 650-volt class and predominantly of the multianode type, but including a few single-anode multitank units. Practices for cleaning and complete inspection of rectifiers and all substation equipment vary in these organizations from six hours once per week to eight hours once per month. Complete overhauls are made at intervals of once per year or longer. Maintenance-cost figures for rectifiers vary widely but were placed at about half that of synchronous converters where comparative data were available.

Recent records of arc-back frequency ranged from two to five per year per rectifier. Increase of arc-back rate above the average for any rectifier has usually indicated some abnormal condition which required correction. Systematic records of arc-backs for each rectifier, by date, have been a valuable assistance in efficient maintenance. Following arc-backs, rectifiers usually are restarted by remote control immediately. D-c feeder short circuits that are cleared with normal speed usually have no adverse effect on rectifier operation.

Experience with multianode rectifiers and single-anode multitank rectifiers on the same system indicates that a maintenance crew should cover about 50 per cent more rectifiers of the latter type in an equal time.

Space and Cost of Rectifier Substations

Preliminary studies of space and cost have been made for several typical substations to determine the effect of the number and size of rectifier units. Dimensions, characteristics, and estimating prices of present-day rectifiers and other substation equipment were obtained. The studies were made on the basis of the following assumed conditions:

Power supply to be at 13,200 volts, 60 cycles. Short-circuit current from the 60-cycle system to be within the interrupting capacity of 500,000-kva circuit breakers on the 13,200-volt side of the rectifier transformers. Direct current to be supplied at 700 volts. Substations to be nonattended and supervisory controlled. Rectifiers, auxiliaries, d-c switching and control equipment, to be in a brick building. Transformers and high-voltage switchgear to be outdoors.

Minimum width of substation was sought by placing the rectifiers and the transformers as close as possible to the end walls for connection through wall bushings. A narrow substation design aids in finding available locations along a railroad right of way. This sort of design applies particularly to suburban transportation. The space limitations of city transit systems often require that all equipment be indoors and that transformers be water-cooled.

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S. S. WATKINS is electrical engineer, Gibbs and Hill, Inc., New York, N. Y.

accompanying line-conductor currents were as low as 2,000 amperes.

11. Where three ground wires were in parallel between the station structure and the first line tower, the lightning currents divided nearly equally between the three wires. The maximum lightning current measured in a single ground wire at stations where three ground wires were in parallel was 10,300 amperes. The maximum current on the line side of the tower where there was only one ground wire was 36,000 amperes.

12. Based on the measured d-c resistance of tower footings, ground rods, and counterpoises, the tower footing is most efficient, 40- to 120-foot ground rods less efficient, and the 250-foot counterpoise least efficient in carrying lightning currents. This conclusion is based on results where the soil is sandy loam and of moderately high resistance.

13. At stations having a large number of connected lines, it appears that comparatively high line-conductor currents rarely are accompanied by sufficient potential to cause arrester operation. At the stations having only two connected lines, numerous instances occurred where arresters operated, but currents in the line conductors were below the limit of registration (1,000 amperes). It is therefore concluded that the presence of several lines at a station reduces the severity of lightning conditions to which apparatus can be subjected.

14. Although the records indicate direct lightning strokes to the transmission system within a mile of the station, there was no case of failure of equipment within the station. It therefore is concluded that the present method of protection by shielding incoming lines and limiting the voltage by lightning arresters at the station has been fully adequate.

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4. MEASUREMENT OF SURGE VOLTAGES ON TRANSMISSION LINES DUE TO LIGHTNING, E. S. Lee, C. M. Foust. AIEE LIGHTNING REFERENCE BOOK, 1918-35. Pages 230-9.

The rectifiers on which the studies were based were in all cases six-phase rectifier assemblies of single-anode tanks. It does not appear that the multitank rectifier design has caused much change in the over-all space requirements of substations. Comparative figures for several sizes and numbers of rectifiers are shown in Table I. Comparison of rectifiers of the same capacity of different manufacture showed considerable differences in over-all dimensions. Space allowances were made to take the largest equipment. Final designs for specific equipment might produce more compact arrangements. However, the space economy of the 3,000-kw rectifiers as compared with the 1,000-kw units is apparent.

Preliminary estimates were made for typical substations exclusive of real-estate cost. To establish a common basis of comparison, a single 60-cycle supply feeder and four d-c feeders were used for each substation, although the number of feeders is apt to be greater in varying amounts in case of application to actual power-supply systems. Cost study results are shown in Figure 1.

Table I. Estimated Space Requirements for Rectifier Substations

Number and Size of Rectifier Units	Building Floor Space: Width and Length	Building Floor Space: Sq Ft	Building Floor Space: Sq Ft Per Kw	Substation Total Ground Space: Width and Length	Substation Total Ground Space: Sq Ft	Substation Total Ground Space: Sq Ft Per Kw
1—1,000 kw	24 by 25	600	0.60	31 by 60	1,860	1.86
2—1,000 kw	24 by 36	864	0.43	31 by 90	2,790	1.40
3—1,000 kw	24 by 49	1,176	0.39	31 by 120	3,720	1.24
1—3,000 kw	24 by 34	816	0.27	31 by 75	2,325	0.78
2—3,000 kw	24 by 61	1,464	0.25	31 by 130	4,030	0.67

Ratings of Rectifiers

Rectifier and transformer combinations are manufactured as co-ordinated designs. Transformers are designed for primary voltage as required by the incoming power supply. Increases in primary-voltage rating affect the cost of rectifier transformers by about the same percentages as in the case of power transformers.

The following overload ratings of rectifier and transformer combinations are generally accepted:

Light duty; 100 per cent load continuously, followed by 150 per cent load for two hours, or 200 per cent load for one minute without injury.

Normal railroad service; 100 per cent load continuously, followed by 150 per cent load for two hours, or 300 per cent load for one minute.

Heavy-duty main-line service; 100 per cent continuously, followed by 150 per cent load for two hours, or 300 per cent load for five minutes.

Transformers are not to exceed 60 degrees centigrade at the end of the two-hour load in these ratings.

Some instances have been noted in operating experience with rectifiers of older design where heavy starting-current swings lasting 15 to 20 seconds have caused arc-back rates to increase. Although rectifier designers are confident that improvements in rectifier design have made those of present manufacture less affected by load swings, it is recommended that load curves and expected swings of starting current be fully discussed with rectifier manufacturers when the capacities of rectifiers for new installation are being determined.

Although rectifier groups of 36 or more phases have been used on heavy-load concentrations in the electrochemical industry, 6-phase and 12-phase rectifiers have been used for railroad service. On only a few railroad installations has interference with communication circuits required the use of filters. D-c filters are relatively inexpensive, filters for the a-c supply circuits are expensive. Rectifiers of more than 12 phases would seldom be justified for railroad service. Six phases are favored unless 12 can be shown to be necessary.

Single-Anode and Multiple-Anode Rectifiers

Single-anode rectifier tanks, assembled as six-phase rectifiers, have been in operation on railroad load of the 650-volt class for about five years. Because of lower arc-drop, single-anode type rectifiers of this class have from one to one and one-half per cent better efficiency than those of the multianode type. The limited amount of railroad experience with single-anode rectifiers favors this type for greater reliability and less maintenance than the multianode type.

Because of wartime regulations, railroad installations have been restricted and therefore railroad experience with single-anode rectifiers has been limited. Greatest experience with this type has been in the electrochemical industry. Here, mass production has stimulated design improvement of single-anode rectifiers. For new installations on railroad load at 700 volts or lower, only the single-anode type is likely to be offered although many years of efficient and reliable operation may be expected of those multianode rectifiers that are now in use.

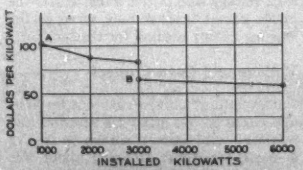

Figure 1. Estimated installed cost of mercury-arc rectifier substations, exclusive of real estate

A. With 1,000-kw units
B. With 3,000-kw units

At 1,500 or 3,000 volts the improvement in efficiency is relatively small for single-anode type rectifiers as compared with the multianode type. Reduced tendency to arc-back, localization of trouble and ability to remove a single-anode tank are advantages remaining in favor of the single-anode type at higher voltage. Opinion is general that the single-anode type will be extended to higher-voltage classes but the degree of present development in that direction varies. For 3,000-volt service, single-anode as well as multianode rectifiers now can be furnished.

Present-day single-anode type rectifiers consist of 6 or 12 tanks assembled on an insulated structural base with vacuum pumps, manifold, and circulating-water pumps common to the assembly. A separate vacuum valve between each tank and the manifold permits any tank to be removed without loss of vacuum in the remaining tanks. It has been found that a 12-tank rectifier can be shut down, a tank removed, a spare tank installed, and the rectifier placed back in operation in about one hour. In some cases, depending upon the recommendations of the manufacturer, a tank may be opened and inspected and returned to normal operation after the establishment of normal vacuum, without the necessity of a bake-out. A desirable feature of some designs is the use of water-cooling on the connection between each tank and the vacuum valve that connects it to the manifold and on the connection between the mercury-vapor vacuum pump and the manifold. Any mercury vapor tending to transfer from either the tank or the pump condenses and drains back to its respective source.

Sealed Steel-Tube Rectifiers

Sealed steel-tube single-anode rectifiers, being permanently evacuated, require no vacuum pumping equipment but are provided with water-cooling to maintain the proper operating temperature. The tubes are assembled in groups of 3, 6, or 12. Connections are three-phase or six-phase, depending on the capacity. They are available as factory-built substations. Sealed-tube rectifiers have had increasing use in industrial and mining applications,

with the greatest volume in the 250-volt class where the single-anode design has a substantial advantage in efficiency over other conversion equipment. The simplicity of these rectifiers, without vacuum equipment and in most cases with raw tap-water connections for cooling, has recommended them in their main fields of application.

These rectifiers are now available for 600-volt service in a six-phase assembly for as high as 1,000-kw total capacity. The simplicity of the sealed tube in the present stage of development is achieved at a sacrifice of operating life of the tube since the internal pressure gradually increases because of effects of the arc. On heavy city transit or suburban service the present maximum size of 1,000 kw is small and tube replacement cost probably would not compare favorably with the maintenance cost of vacuum-pumped equipment where skilled personnel is available.

However, the possibilities of sealed-tube rectifiers deserve some consideration in the case of lighter transit systems. It has been suggested that these rectifiers have a field of application on 600-volt trolley-coach systems requiring small power-supply units. Steel cubicles containing the tubes might be placed outdoors and provided with heaters and outdoor cooling equipment for keeping operating temperatures within proper limits. The cost of such a design, assembled with the transformer and the a-c and d-c switching as a unit outdoor substation, in ratings up to 1,000 kw, might compare favorably with that of conventional arrangements of indoor equipment in a building.

Switching Equipment

Switching equipment on the high-voltage side of the rectifier transformers is of conventional types. Circuit-breaker voltage class and interrupting rating are determined by the characteristics of the supply system. One high-voltage circuit breaker is required for each rectifier unit. The number of additional incoming feeder circuit breakers depends on considerations of service continuity and over-all system design. Connection of each rectifier transformer through a single circuit breaker direct to the power-supply system may be used to advantage where the latter system is sufficiently reliable. The transformer supplying the substation and rectifier auxiliaries must be connected so that its supply is not interrupted by opening of the rectifier-transformer circuit breaker. When power supply is at 13,200 volts or less, outdoor metal-clad switchgear makes an effective switching arrangement.

High-speed (one-cycle) air circuit breakers between the rectifier cathode and the d-c bus are used in 3,000- and 1,500-volt substations and in many substations of the 650-volt class. These circuit breakers are automatic on reverse current and, in case of arc-back, interrupt the reverse feed from the d-c system. There is a tendency, at present, to use semi-high-speed air circuit breakers in the cathode connection where the total continuous capacity on a 650-volt bus is less than 9,000 amperes but to use high-speed switching wherever the capacity on the bus is above 9,000 amperes or where synchronous converters operate in parallel with rectifiers on the same bus.

The choice of high-speed switching for the 650-volt rectifier has been widened by the development of high-speed air circuit breakers for connection between rectifier anodes and transformer secondary. These circuit breakers usually are six-pole, consisting of six single poles each with individual reverse-current tripping device. The six poles operate together as a unit on closing. The location of these circuit breakers is such that all current contributions to an arc-back are interrupted by the opening of one circuit-breaker pole. Tests of these circuit breakers on arc-backs have shown that reduction of current magnitude starts in less than one half cycle and that interruption is complete in less than one cycle. Previous to the use of high-speed anode circuit breakers, although back feed from the d-c bus to an arc-back was interrupted within one cycle, the current contributed by other phases of the same rectifier was not interrupted until about eight cycles later by the circuit breaker on the high voltage side of the transformer. Anode circuit breakers have been a product of necessity for protection against the possible destructive effects of short circuits in the electrochemical industry where the concentrations of current on a single bus are many times those encountered in railroad service.

When high-speed anode circuit breakers are used, semi-high-speed circuit breakers may be used in the cathode connection. This combination should be favorably considered wherever high-speed switching is required for rectifiers in the 650-volt class. High-speed anode circuit breakers afford ideal protection.

Wherever, in the over-all design of the incoming power supply system, it is possible to eliminate circuit breakers on the high-voltage side of the transformers the anode circuit breaker may serve as the starting circuit breaker for the rectifier.

Voltage and Load Control

The natural unregulated output-voltage curve of the usual transformer and rectifier combination is similar to that of a shunt generator, drooping about five per cent. This characteristic assists in division of load between substations and has been preferred on a majority of installations. Where a flat-compound characteristic is desired, it can be accomplished by delaying the start of current conduction through each anode to the extent necessary to counteract the rise of output voltage with decreasing load. In this case the transformer and rectifier must be designed with a natural characteristic to provide a voltage above that for which the rectifier is to be regulated. Delayed conduction, called phase control, increases d-c ripple and increases distortion of the voltage wave of the a-c supply. Power factor is decreased by about the same percentage as the reduction in voltage below the unregulated value. Both these effects are greatest at the lightest loads when phase control is used for compounding.

Phase control may be accomplished by timing the removal of negative bias from a control grid located in the arc path. In an ignitron type of single-anode rectifier employing the saturable-reactor ignition circuit, operation of a rheostat in a d-c coil circuit changes the time characteristic of the circuit and controls the timing of rectifier ignition. In standard designs a range up to 15 per cent voltage reduction is available by adjustment. Circuits can be designed for greater than 15 per cent voltage reduction but this is not usually advisable or necessary.

Voltage control by the methods described may be accomplished manually by a load dispatcher if the control rheostat is motor-operated through the medium of supervisory control. By this means, rectifier output voltages may be adjusted for a desired division of load between different sources of a-c supply.

If automatic regulation is desired, a voltage regulator may be used to operate the ignition-timing rheostat. The compounding characteristic may be designed for similarity with that of existing compound-wound apparatus where parallel operation is required. Where automatic load limiting is required, the ignition-timing rheostat may be put under the supervision of an output-current relay so as to reduce output voltage as a limiting load is approached. This feature may serve power-purchase policy in avoidance of demands above a given limit or it may be used to prevent overloading particular substations above a set limit.

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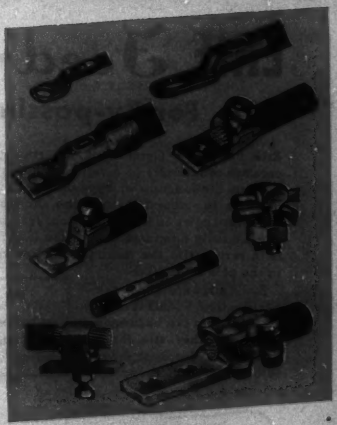

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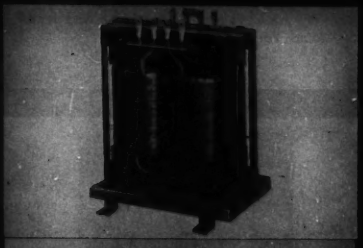

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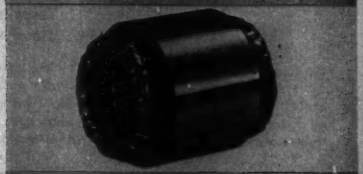

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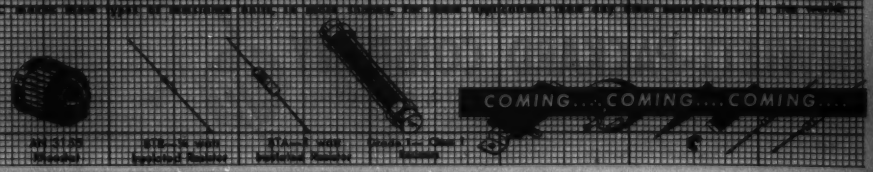

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Fiberglas is glass in fiber form—as such, it retains part of the characteristics commonly associated with glass. And, because of its form, fibers finer than human hair, it gains several desirable characteristics which make it an unsurpassed insulating material when properly impregnated. In textile form Fiberglas provides a thin, strong, flexible, inorganic fabric base for insulating impregnants. This combination has unexcelled advantages and characteristics, and is available in Magnet Wire, Lead Wire, Special Wires and Cables, Varnished Cloth and Tape, Mica Combinations, Laminates, Saturated Sleeving, Varnished Tubing, Pressure-Sensitive Tapes and special products.

Anyone concerned with the specification or application of electrical insulation should have a copy of the new Fiberglas Electrical Insulation Material Catalog for ready reference . . . it tells what type to use, where and how. Write for your copy today and ask for the name of the Fiberglas Electrical Insulation Material supplier nearest to you . . . *Owens-Corning Fiberglas Corp., 1859 Nicholas Building, Toledo 1, Ohio. In Canada, Fiberglas Canada Ltd., Oshawa, Ontario.*

FIBERGLAS combats these common enemies

Fiberglas provides all of the advantages of an inorganic material yet it has high tensile strength and an unusually favorable space factor.

MOISTURE. The individual fibers do not absorb moisture. They will not swell or disintegrate or become chemically affected through moisture contact.

HEAT. In textile form with close contact of fiber on fiber, Fiberglas has high heat conductivity and removes heat from "hot spots" to cooler areas where it is dissipated.

CORROSIVE CHEMICALS. Glass is not attacked by most corrosive vapors or acids. Fiberglas, therefore, provides an exceptionally durable support for the impregnant even under adverse conditions.

THE HUMAN ELEMENT. The added protection afforded by Fiberglas can frequently minimize or offset losses and failures, due to carelessness, lack of maintenance time and skill.

Write for your copy of the new Fiberglas catalog today.

BE SURE TO SEE THE FIBERGLAS ELECTRICAL INSULATION MATERIAL EXHIBIT *THE NEXT SHOWINGS ARE:* Copley Plaza, Boston, January 24-26; Bellevue Stratford, Philadelphia, January 30-February 2; Belvedere, Baltimore, February 7-8; Hotel Statler, Washington, February 14-15; Hotel Roosevelt, Pittsburgh, February 19-21; Hotel Statler, Buffalo, February 27-March 1. Further showings will be announced later.

ARMY E NAVY

FIBERGLAS ELECTRICAL INSULATION MATERIAL

®T. M. Reg. U. S. Pat. Off.

Sensitive
SNAP-ACTION
...in a new, simplified design

A TYPICAL CLOSE DIFFERENTIAL APPLICATION

In using the Struthers-Dunn 79XAX Relay, extremely close differential between pick-up and drop-out may be obtained for potential operation as shown above. The resistor is chosen so that, when the armature closes, the coil current is automatically reduced to a value just sufficient to hold it closed. Any further decrease in voltage will cause the relay to return to its normal de-energized position as shown.

The new, simplified construction of the Struthers-Dunn Type 79XAX Sensitive Snap-Action Relay makes it particularly suitable for a wide range of applications because of its ease of adjustment. Snap-action design assures full normally-closed and normally-open contact pressures. Erratic operations and varying contact resistance encountered with ordinary sensitive relays, due to slowly changing coil flux balancing armature spring tension, are eliminated.

The armature of the 79XAX almost completes its travel in either direction before the contacts snap into the new position. This feature permits an unusually broad range of use from vacuum tube circuits, to overcurrent protection, pulsing circuits, and jobs where extremely close differential or extreme sensitivity of operation is required.

The standard adjustment using 60 ampere turns in the coil at approximately .02 watts results in contact pressures of 5 grams with contacts rated 5 amperes, 115 volts a-c; or 0.5 amperes, 115 volts d-c, non-inductive. Contact ratings up to 10 amperes, 115 volts a-c may be obtained with 100 or more ampere turns and a corresponding increase in power. A sensitivity of 0.005 watts, with 30 ampere turns, is obtainable with reduced contact pressures and ratings, and at an increase in price of the unit.

STRUTHERS-DUNN INCORPORATED
1321 ARCH STREET, PHILADELPHIA 7, PA.

STRUTHERS-DUNN

ATLANTA · BOSTON · BUFFALO · CHICAGO · CINCINNATI · CLEVELAND
DENVER · DETROIT · HARTFORD · INDIANAPOLIS · LOS ANGELES · MINNEAPOLIS · MONTREAL
NEW YORK · PITTSBURGH · ST. LOUIS · SAN FRANCISCO · SEATTLE · SYRACUSE · TORONTO · WASHINGTON

SMOOTH COMMUTATION!

A.C. VOLTAGE CONTROL with TH 2½A TRANSTAT

Brush Arm Assembly

One piece die casting permits good heat dissipation, provides a simple means of replacing the brush and protects the commutator against contact with brush holder if brush should break or loosen.

Core and Coil Impregnated FOR Long Service

Each turn of vinyl coated insulated wire is PERMANENTLY anchored by impregnation of whole core and coil with phenolic resin, followed by baking.

Broad Commutating Surface

Ground from parallel wires on outer periphery of coil, forms long even segments with solid insulation necessary to avoid shorted turns. Greater contact area results in a lower operating temperature. Smooth, mirror-like finish provides a practically frictionless brush track.

Write FOR THIS NEW FOLDER!

Complete description, including construction details, performance curves, wiring diagrams, ratings, electrical data and applications covered. Ask for Bulletin No. 171-01.

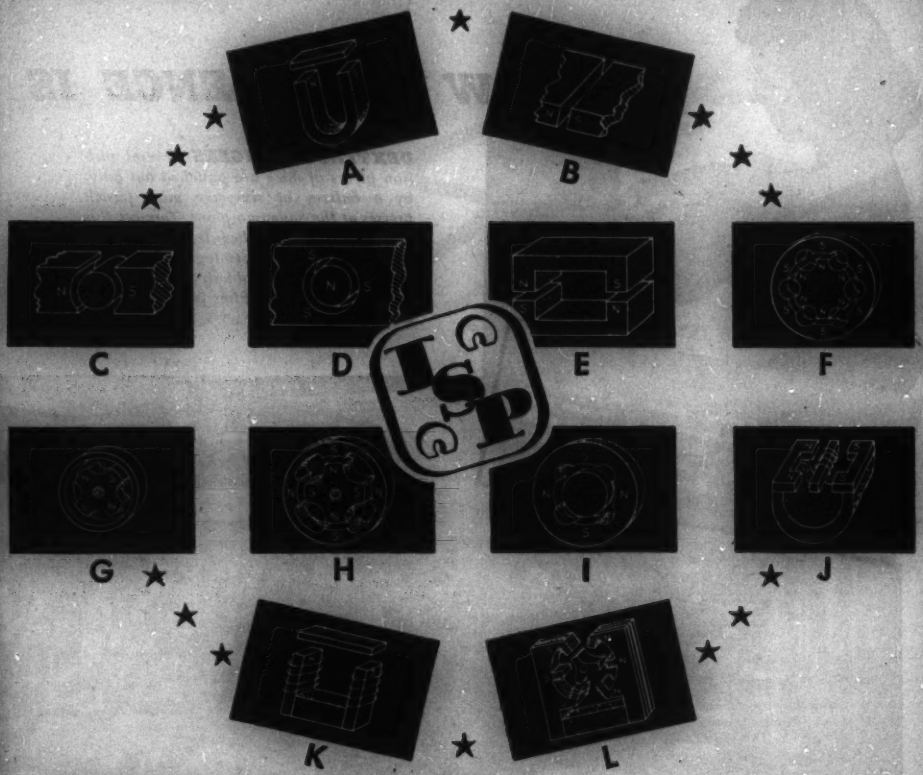
AMERICAN TRANSFORMER COMPANY
178 Emmet Street, Newark 5, N. J.

AMERTRAN

Pioneer Manufacturers of Transformers, Reactors and Rectifiers for Electronics and Power Transmission

AMERTRAN

PERMANENT MAGNETS MAY DO IT BETTER



Basic Types of Air Gaps

The space required for a magnetic field is known as an "air gap." Most of the fundamental types of air gaps are illustrated above—from the familiar form shown in "A," which is simply a permanent magnet with an armature adjacent to the poles of the magnet, to the inductor type alternator such as type "L."

The basic forms of permanent magnets and their associated air gaps are subject to infinite variations. They are used in a rapidly growing number of applications . . . potentially, there are unlimited uses for permanent magnets as yet undiscovered.

In specializing in permanent magnets since 1910, we have discovered and engineered many advances in magnetic technology with the result that this company is now the largest in the country manufacturing permanent magnets exclusively.

If you are making products which might function better through the employment of magnetic energy, our engineers will be pleased to consult with you. Write for complete information. Ask for a copy of *"Permanent Magnets Have Four Major Jobs."*

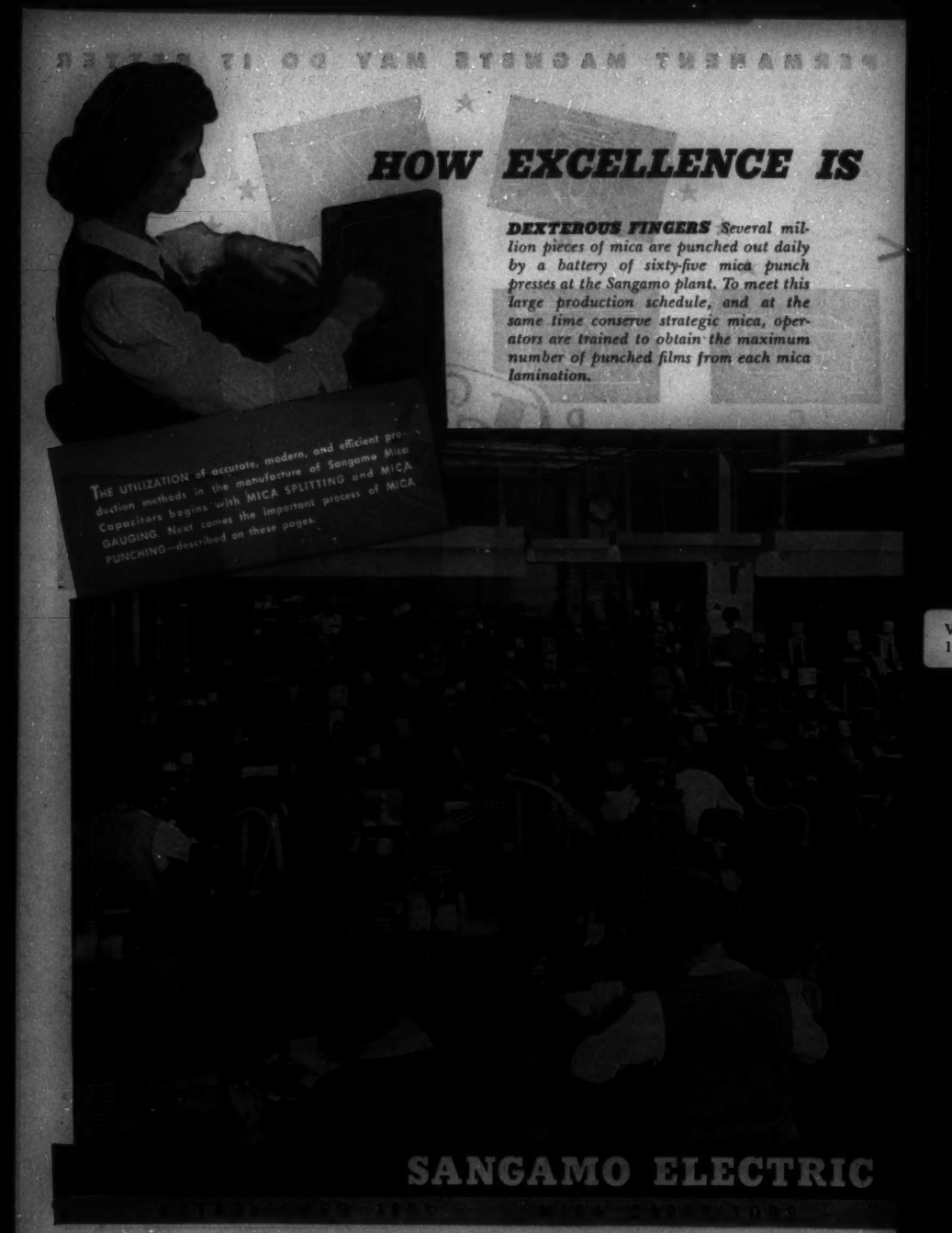
THE INDIANA STEEL PRODUCTS COMPANY

6 NORTH MICHIGAN AVENUE • CHICAGO 2, ILLINOIS

ARMY E NAVY

Specialists in Permanent Magnets Since 1910

COPYRIGHT 1945, THE INDIANA STEEL PRODUCTS COMPANY


HOW EXCELLENCE IS
DEXTEROUS FINGERS Several million pieces of mica are punched out daily by a battery of sixty-five mica punch presses at the Sangamo plant. To meet this large production schedule, and at the same time conserve strategic mica, operators are trained to obtain the maximum number of punched films from each mica lamination.
THE UTILIZATION of accurate, modern, and efficient production methods in the manufacture of Sangamo Mica Capacitors begins with MICA SPLITTING and MICA GAUGING. Next comes the important process of MICA PUNCHING—described on these pages.
SANGAMO ELECTRIC

BUILT INTO . . . .

Sangamo

MICA CAPACITORS

★

Mica Punching

★

The great number of case sizes in which Sangamo Mica Capacitors are manufactured necessitates a large variety of sizes and shapes of mica films. Mica, as produced in nature, has no semblance of uniformity, consequently it must be fabricated to the desired size and shape. Mica is a hard brittle material requiring the use of specially designed dies to insure a finished film with sharp, clean edges and free from fractures.

Thus, only by maintaining constant vigilance in each of the manufacturing processes, is it possible to produce a capacitor capable of giving long and dependable service under the severe operating conditions encountered by modern electronic equipments.

COMPANY SPRINGFIELD ILLINOIS

RAYTHEON VOLTAGE STABILIZERS

INSURE ACCURATE OPERATION of ELECTRICAL EQUIPMENT

Stabilize Varying Input Voltage Within 2 Cycles to Constant Output Voltage at ±½ of 1%

Raytheon Voltage Stabilizers, incorporated into electrical equipment, insure accurate, dependable operation by providing stabilized A. C. voltage to ±½ of 1%. They are available in three designs . . . uncased, cased and endbell . . . to meet every installation requirement whether it is to be built into new equipment or products already in use. Entirely automatic in operation, it is ideal for equipment in unattended locations.

Write for Bulletin DL48-537. It gives the complete story.

TIME CONSTANT

Transient changes in output voltage result from variations in line voltage. These transients disappear entirely in 6 cycles. The major effect of the transient recovery is practically complete in 2 cycles. These changes are not evidenced on a volt meter of normal characteristics and their behavior is usually unimportant. Transients resulting from connecting or disconnecting the load require somewhat longer time for recovery. Smaller changes in load cause proportionately smaller transient disturbances in output voltage. This characteristic is shown above.

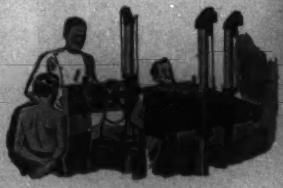
Tune in the Raytheon radio program "MEET YOUR NAVY", every Saturday night on the Blue Network. Consult your local newspaper for time and station.

RAYTHEON
MANUFACTURING COMPANY
190 WILLOW STREET · WALTHAM · MASS

The coveted Army-Navy "E", for Excellence in the manufacture of war equipment and tubes, flies over all four Raytheon Plants where over 16,000 men and women are producing for VICTORY.

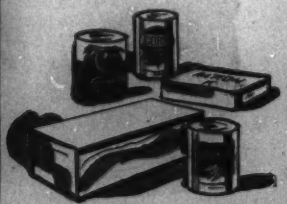
WONDER-WORKING WITH ELECTRONS

BOMBERS FROM THE BOTTOM OF THE SEA . . . There's a fabulous amount of magnesium . . . enough for 4,000,000 Flying Fortresses . . . in every cubic mile of sea water. To extract this vital metal from the ocean, vast quantities of d-c electricity are needed. An electronic device, the Westinghouse Ignitron, supplies this current by changing a-c to d-c — *right at the water's edge.* Ignitrons, with a combined capacity of more than 3,000,000 kilowatts, are now at work in magnesium, aluminum and chlorine plants, in electric railway systems, in mines, in many war industries.



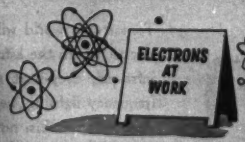
A NEW X-RAY machine, built by Westinghouse, makes possible the examination of 1000 school children daily — for symptoms of tuberculosis. X-ray pictures are taken by a 35 mm candid camera — at a cost of less than 1¢ per exposure.

DUST TAKES A HOLIDAY . . . Dust-free air is absolutely essential in the assembly of optical equipment for our fighting forces. The Westinghouse Precipitron* electronic air cleaner automatically removes dust particles down to the size of 1/250,000th of an inch.



S-T-R-E-T-C-H-I-N-G THE TIN SUPPLY . . . Electronic high-frequency induction heating — developed by Westinghouse — helps save *two-thirds* of our war-scarce tin supply by flowing a protective tin coating, only 30-millionths of an inch thick, on steel strip.

ELECTRONIC CHEMIST . . . The Westinghouse Mass Spectrometer analyzes intricate gas mixtures at amazing speed. In making synthetic rubber, for example, this electronic device cuts the time of chemical analysis from days to a matter of minutes.



Although one of the tiniest things in the universe, the electron is a gigantic force for the good of mankind. It is helping us to win the greatest war in history. It speeds production of goods for war and peace . . . brings entertainment into our homes . . . contributes to our health and happiness in countless ways. *And wherever you find electrons at work you will find Westinghouse electronic research at the forefront!*

*TRADE MARK REG. U.S. PAT. OFF.

SOMETHING TO CROW ABOUT . . . The Westinghouse Sterilamp*, an electronic device, deals sudden death to air-borne bacteria in brooder batteries — has reduced chick mortality by 50%. Sterilamps are widely used in restaurants, canneries, breweries, and many other industries.

Tune in:
JOHN CHARLES THOMAS
Sunday 2:30 pm, EWT, NBC

Westinghouse
PLANTS IN 25 CITIES OFFICES EVERYWHERE

Tune in: TED MALONE
Mon. Tues. Wed. Evening, Blue Network

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US

Serving Through Science

Listen to "Science Looks Forward"—new series of talks by the great scientists of America—on the Philharmonic-Symphony program. CBS network, Sunday afternoon 3:00 to 4:30 E.W.T.

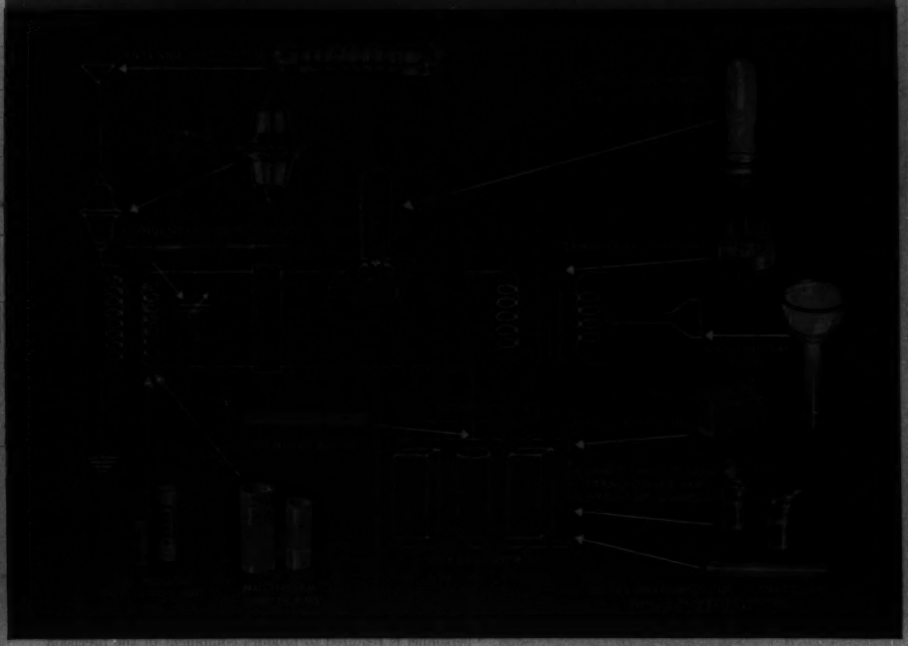
Tomorrow's world will witness countless new home benefits from electricity. In the kitchen, new quick-freeze refrigerators and new infra-red, deep-heat stoves—throughout your house, new high-frequency lighting, new FM and television radios. And to deliver electricity for this, not the ordinary wire of today, *but a new wire, with new and higher electrical standards will be required.*

Scientists have pioneered a better insulation for just such a wire. Through research that stems from the rubber molecule itself, and through precise methods of production, United States Rubber Company has developed Nubun...a new buna rubber insulation, flexible, moisture-resistant, tough—safe. Nubun is applied by the unique dipped process that permits perfect centering of the wire and a diameter smaller than any now commercially available.

UNITED STATES RUBBER COMPANY

1230 Sixth Avenue, Rockefeller Center, New York 20, N. Y. • In Canada: Dominion Rubber Co., Ltd.

ARE YOU LETTING GLASS HELP YOU ALL IT CAN?



It wouldn't be surprising if you aren't familiar with everything glass is doing in electronic equipment today. Progress has been rapid. In the above *"circuit"*, for example, you'll find it on the job in (twelve) vital places. At Corning right now we're making a lot of other electronic glassware that we can't show. After the war we'll tell you all about it.

It's no accident that a major part of the electronic glassware in use got its start at Corning. We've dug in on some tough ones and ferreted out solutions. They told us we couldn't solder metal to glass — they needed glasses with a coefficient of expansion practically equal to that of fused quartz —they needed something to take the place of mica in capacitors — Corning Research found the answers to these and many other electronic problems.

Our 250 glass experts—the men behind "Corning Research"— our facilities and all our knowledge of glass are at your service. Write for a copy of an informative new booklet "There Will Be More Glass Parts in Postwar Electrical Products." Address Electronic Sales Dept. N-2, Bulb and Tubing Division, Corning Glass Works, Corning, N. Y.

CORNING *means* Research in Glass

Electronic Glassware

"PYREX" *and* "CORNING" *are registered trade-marks of Corning Glass Works*

GENERAL RADIO was granted the coveted Army-Navy "E" Production Award for the fifth time in December of last year. G-R is one of very few in the electronic industry to receive this honor five times.

The production of precision electrical test equipment is a highly specialized business, demanding maintenance of close tolerances in all inspection, manufacturing and calibrating operations. Constant and close supervision by highly trained personnel is required to produce equipment of the precision and reliability of G-R instruments.

In order to meet the greatly increased production called for by the war, G-R has expanded to its limit, both in space and in personnel. We have subcontracted machining operations to several local firms; we have transferred our entire VARIAC production to leased space in another building; we have obtained considerable space in another building where we have contracted for a large number of war-time workers under our own foremen; we have let out the complete manufacture of several instruments to other manufacturers; we have turned over the design, drawings and models of several critical instruments to other manufacturers for their exclusive use.

G-R is proud that it has been able to meet the urgent production requirements of the war effort. It is equally grateful that the substantial contributions from its Development and Engineering Departments, through many thousands of hours of consulting engineering on secret war projects, have directly assisted in the soluton of technical problems of the greatest urgency.

GENERAL RADIO COMPANY Cambridge 39, Massachusetts
NEW YORK CHICAGO LOS ANGELES

No Plant Too Large *or too small* To Profit by this SQUARE D *Conversion Plan!*

● Panelboards, taxed beyond their efficient capacities, are a drain on the productivity of any plant — regardless of its size. This speedy Conversion Plan involves such a moderate investment that it "pays off" in a hurry, even in the smallest plant.

The pictures above show a typical conversion. With a minimum of time and labor and at no increase in space, 25 lighting circuits were increased to 42—up 68%. Circuit breaker convenience and protection replaced obsoleted fusible circuits. Notice, too, that Saflex units were installed for the main controls, with sufficient space provided for an additional circuit, if and when it is needed.

Remember, such conversions as these utilize existing boxes and conduit. The cost in time and money is small. The dividends in conserved power and increased efficiency are substantial. Your nearby Square D Field Engineer will be glad to analyze your present equipment and submit a tailor-made conversion plan for your consideration. This service costs nothing—pays big dividends.

Write for a free copy of "MORE CAPACITY" which shows a variety of conversions in detail. Address Square D Company, 6060 Rivard Street, Detroit 11, Michigan.

SQUARE D COMPANY

DETROIT • MILWAUKEE • LOS ANGELES

LABORATORY VOLTAGES accompany your equipment into the field with built-in CONSTANT VOLTAGE

On the drafting boards of hundreds of sales-minded design engineers, product insurance is being written into the specifications of new electronic and electrically operated equipment.

A critical analysis of sales department records of past performance usually discloses that the most frequent cause of equipment failure or sub-standard performance is the one most often overlooked—field voltages that do not correspond to the rated voltage at which the equipment is designed to operate.

Today sales-minded design engineers make certain that carefully controlled laboratory voltages, on which the operation of their equipment is predicated, go with it into the field, by writing "SOLA Constant Voltage Transformers" into their design specifications. In many cases the inclusion of the "CV" transformer is accomplished at an actual saving in cost over standard equipment design.

Thus rated voltage is available at all times because SOLA Constant Voltage Transformers instantly correct fluctuations as great as 30% to less than ±1% of rated requirements. These sturdy, automatic transformers require no pampering or supervision. They protect both themselves and the equipment against line surges and short circuits.

Standard units are available in capacities from 10VA to 15 KVA or special units can be built to your specifications.

SOLA Constant Voltage Transformers

Don't forget to write for Sola's new Bulletin
Ask for Bulletin ACV-102

Transformers for Constant Voltage • Cold Cathode Lighting • Mercury Lamps • Series Lighting • Fluorescent Lighting • X-Ray Equipment • Luminous Tube Signs Oil Burner Ignition • Radio • Power • Controls • Signal Systems • Door Bells and Chimes • etc. SOLA ELECTRIC CO., 2525 Clybourn Ave., Chicago 14, Ill.

HOW TO SELECT PHOTOTUBES

PHOTOTUBES have found such a wide variety of applications that many types have been developed to meet special needs. The complete RCA line includes both gas-filled and high-vacuum phototubes, with various spectral responses and a variety of sizes and shapes. And for applications requiring extreme sensitivity, RCA supplies multiplier phototubes.

A phototube acts as a light-actuated electric valve. (It does *not* convert light energy to electrical energy, but acts only as a control device.) The current passed is in proportion to incident light. Some phototubes are "high-vacuum" types; some are filled with an inert gas (such as argon) to increase current-carrying capacity.

A multiplier phototube contains additional electrodes (dynodes) which emit secondary electrons and thus greatly increase sensitivity and output current as compared to 2-electrode phototubes.

Color Sensitivity: The cathode coating material and the envelope glass determine color sensitivity. RCA phototubes fall into five "color groups":

Use	Tube Types	Maximum Color Sensitivity
With incandescent lamps	High vacuum: 925, Gas-filled: 868, 930, 934, 927*, 928	Red and infra-red
With incandescent lamps—and for infra-red application	High vacuum: 917, 919, 922*, Gas-filled: 918, 931*, 933, 950*	Similar to above, but sensitivity extended further into infra-red
With light source for colorimetry application	High-vacuum: 926	Blue light. Approximates the human eye
With daylight, carbon-arc, or mercury-vapor light source	High-vacuum: 929*, 954, Multipliers: 931-A*, 1P21	Blue light. Very sensitive to incandescent light at a color temperature above 2700°K.
For ultra-violet measurement	High-vacuum: 935, 1P28	Same as above, but special glass envelope permits high ultra-violet sensitivity

*An RCA Preferred Type Tube

Color response curves are available on all RCA phototubes.

Vacuum- or Gas- or Multiplier-Type? Several important factors to be considered in selecting the general type of phototube for a service are given in the following table. Specific values should be considered in selecting the actual tube type.

Characteristic	High-Vacuum type	Gas-filled type	Multiplier type
Sensitivity	Low	Medium	Very high
Current Output	Low	Medium	Very high
Amplification factor	1	Up to 10	Up to 1,000,000
Relative signal-to-noise ratio (including amplifier stage)	Low	Intermediate	High
Anode Volts	Up to 300	Not over 90	Up to 1250
Distortion (audio)	Negligible	Appreciable in some cases	Negligible
Frequency Range	Limited largely by circuit	Limited by tube performance	Limited largely by circuit

Gas-filled phototubes are, at present, extensively used for sound-on-film reproduction and for relay work. Vacuum-types are widely used where high sensitivity is needed; for precision measurement where stability of calibration is essential; and for high-speed work.

Sensitivity: The sensitivity of a phototube may vary according to whether the light change is abrupt or continuous. *Static sensitivity* is the ratio of anode direct current to constant light flux. *Dynamic sensitivity* is the ratio of the variation of anode current to the variation of light input. The sensitivity of gas-filled phototubes drops off as light-source frequency increases.

Optical Systems: The use of phototubes usually involves some sort of optical system. The fundamentals of optics must be carefully considered in the successful application of phototubes.

Mechanical Features: As illustrated at left, several types of tubes are available. Size, vibration, directional requirements, etc., all may influence the choice of one of the many RCA phototubes.

Phototube Life: Phototubes are inherently sturdy, long-lived tubes and when operated under recommended conditions, give extended reliable service.

Application Hints: Here are a few general suggestions on applying phototubes:

1. In relay and measurement circuits where tubes must respond to very small amounts of light, avoid leakage currents outside tube. Keep tube terminals and sockets clean. Erratic leakage currents will affect results.
2. In amplifiers where low leakage is important, select top cap types such 917, 919, or 935.
3. Shield phototube and leads to amplifier or relay tubes when amplifier gain or phototube load resistance is high.
4. Where high-frequency response is important keep phototube leads short to minimize capacitance shunting of output.
5. For constant calibration of high-precision vacuum phototube devices, keep anode voltage at or below 20 volts. Keep incident light spread over wide cathode area.
6. Design or circuit constants should be based on tests with the equipment operating over the expected range of line-voltage variation.
7. RCA voltage-regulator tubes can improve phototube circuit performance.
8. Anode characteristic curves on phototubes can be used to predict performance under given operating conditions.

What Phototube Do You Need? Due to space limitations, the suggestions presented here are brief and in a condensed, summary form. If you have a specific application problem or wish to discuss your phototube requirements with us, write to RCA, Commercial Engineering Section, Dept. 62-27A, Harrison, N. J. For further published information on RCA Phototubes and how to use them, send the coupon at left.

Send for this valuable data

FREE!

Free to electronics engineers: "RCA Phototube Booklet," complete with 11 typical circuit diagrams, curves, tables, and clearly written text. Address: RCA, Commercial Engineering Section, Dept. 62-27A, Harrison, N. J.

Please send free phototube data to:

Name .....

Company .....

Address .....

City ..... State .....

RADIO CORPORATION OF AMERICA

RCA VICTOR DIVISION . CAMDEN, N. J.

The Name Brand of all electronic equipment is a Tube of the finest kind of modern Tube development is RCA.

"DUSTLESSTOWN, OHIO"

● It's the little things that loom biggest in the manufacture of delicate electrical measuring instruments. Little things like specks of dust or breath condensation can play havoc with accuracy. That's why Triplett Instruments are made in spotless manufacturing departments; why the air is washed clean, de-humidified and temperature-controlled; why every step in their mass production is protected. As a result Triplett Instruments perform better, last longer and render greater service value.

Extra Care in our work puts Extra Value in your Triplett Instrument.

Precision first ...to last

Triplett

STANDARDS ARE SET BY TRIPLETT

ELECTRICAL INSTRUMENT CO. BLUFFTON, OHIO

a NEW *Industrial* POWER TUBE *by* Federal

TECHNICAL DATA FOR TYPE F-5303

Filament Voltage	11.0 volts
Filament Current	27.5 amps.
Maximum Ratings for Maximum Frequency of 50 Mcs.	
DC Plate Voltage	3500. volts
DC Plate Current	1.0 amp.
Plate Dissipation	1200 watts
Overall Height	app. 7"
Maximum Diameter	3¾"
Supplied with 6 flexible copper leads, 2 on each terminal.	
Type of Cooling	Forced-air
(Also supplied for water-cooling, type F-5302.)	

Federal presents a new and rugged power tube that fills an immediate demand — a power tube that has been *specially* designed for industrial use in high-frequency heating equipment, both dielectric and induction.

Really built to withstand the constant jars, shocks, and vibration commonly encountered in manufacturing operations, this heavy-duty vacuum tube is very conservatively rated, and will stand up under extremely hard usage.

Widely spaced, unusually sturdy filament and grid elements, without internal ceramic insulation, give this tube a ruggedness that makes it the logical choice for dependability in the design of industrial heating equipment.

For industrial power tubes, and also for rectifier and transmitting tubes, see Federal first... because "Federal always *has* made better tubes."

FTR — Federal Telephone & Radio

Federal Telephone and Radio Corporation

A Unit of IT&T System

Newark 1, New Jersey

THERMEX meets the demand for high frequency equipment for pre-heating of plastic preforms. Preforms are placed on this drawer which slides into unit shown below.

THERMEX MODEL 2-P

Of course it uses Eimac tubes

This compact Thermex unit measures 28 inches by 28 inches, stands 47 inches high, and weighs only 614 pounds. It is a practical and flexible piece of equipment with built-in heating cabinet and removable 12 inch by 15 inch drawer-electrode.

Being completely automatic, there is nothing to do but plug this Thermex in and load and unload the preform drawer. No dials, no tuning, not even a button to push. Closing the preform drawer all the way in, turns on the high frequency power and timer. At the end of the prescribed time, which may be anywhere from 5 to 10 seconds up to 2 minutes, the red indicating light goes out, the operator removes the tray and unloads the preforms into the mold cavities.

The Thermex Model No. 2-P, which is illustrated, operates at a frequency of 25 to 30 megacycles using 230 volt 60 cycle single phase current. It has an output in excess of 3400 BTUs per hour, and it uses a pair of Eimac 450-TH tubes. The use of electronic heating has increased production for many plastic manufacturers who have been leaders in utilizing the science of electronics.

The Thermex Division of the Girdler Corporation of Louisville, Ky., is a leader in supplying equipment for this and other industrial applications. It's natural that Eimac tubes are used, since these tubes are first choice of leading electronic engineers throughout the world.

Follow the leaders to

Eimac REG. U. S. PAT. OFF. **TUBES**

EITEL-McCULLOUGH, Inc.
985 San Mateo Avenue, San Bruno, California

Plants located at: San Bruno, California and Salt Lake City, Utah
Export Agents: Frazar & Hansen, 301 Clay St., San Francisco 11, California, U. S. A.

Eimac has received 7 ARMY-NAVY "E" AWARDS for production efficiency • San Bruno 3, Salt Lake City 2

Introducing "Control Gaging"—A New Technique

EXPERIENCE spot-lighted the necessity for gaging *at the machine* by which the operators themselves could quickly detect any tendency towards "out-of-control" running.

Setting go-no-go gages at the specified tolerance was ineffective. Studies resulted in development of a simple technique which we have called "control gaging."

This new technique, now used by Hunter on all control-charted operations, has proved very efficient. On short-run, close-tolerance jobs, where control charting cannot be effectively applied, control gaging obtains a degree of control comparable with long-run control-charted jobs.

In control gaging, the setting of the gages is determined by a simple mathematical analysis of samples from the machine. While running, the operator draws 5 pieces *produced in succession*, passes them through the control gage, and notes the number of failures at both limits. If, for example, over 2 pieces fail at the high limit the machine is running to the high side. A combination of low and high failures exceeding 3 pieces indicates the range has increased.

Suppose a machine is producing parts with a tolerance of ± .003". Now assume the machine setting shifts so that production is running + .004" — .002". The machine operator has only one chance in 44 of detecting the shift using conventional gage limits. Control gages, however, would definitely show the machine was off center through an increase in number of gage failures (beyond the 2 high max.) to 26% of the lots checked. The ratio of efficiency is at least 10/1 in favor of the control gage method.

THIS PROBLEM *posed in the last paragraph above is illustrated by the models below. The heights of the bars show the relative frequencies with which control gage limits are exceeded. Note the strong positive shift in these frequencies with off-center running. Control gage setting for sample size* $5 = \bar{X} \pm .577\,\bar{R}$. *If you are not already acquainted with statistical methods for quality control we recommend that you promptly obtain copies of ASA Bulletins Z1.1-1941, Z1.2-1942 and Z1.3-1942 from the American Standards Association, 29 West 39th Street, New York, N. Y.*

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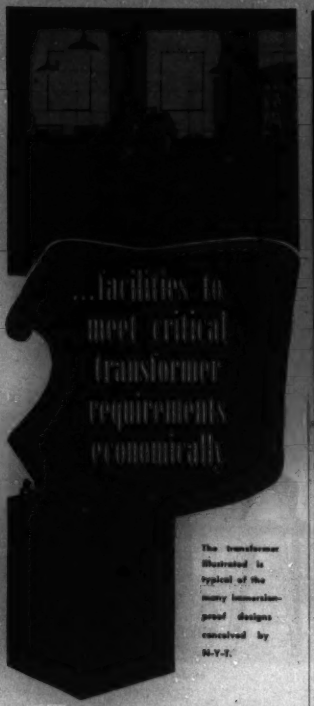
Transmitting Tubes and Vacuum Condensers

PHOTOGRAPH SHOWS OPERATION OF ROTARY BASING MACHINE FOR JENNINGS CAPACITORS



The transformer illustrated is typical of the many immersion-proof designs conceived by N-Y-T.

With current deadline and delivery factors steadily being overshadowed by sharpened pencil cost considerations, fluctuations in price structure will be in evidence. Adjustment for post-war necessities will, in all probability, be on a downward trend without sacrifice of quality or reliability.

From its inception, N-Y-T has 'majored' in the design of transformers, chokes, filters and solenoids, custom-engineered to meet specific requirements. Aside from meeting exacting requirements, all phases of production—collaboration, design, and manufacture—were 'in line' relative to cost.

This same policy—currently adhered to—is credited with numerous solutions in vital military design problems. Manufacturers projecting peacetime plans should keep in mind the record of N-Y-T in accomplishing 'impossibilities' . . . economically.

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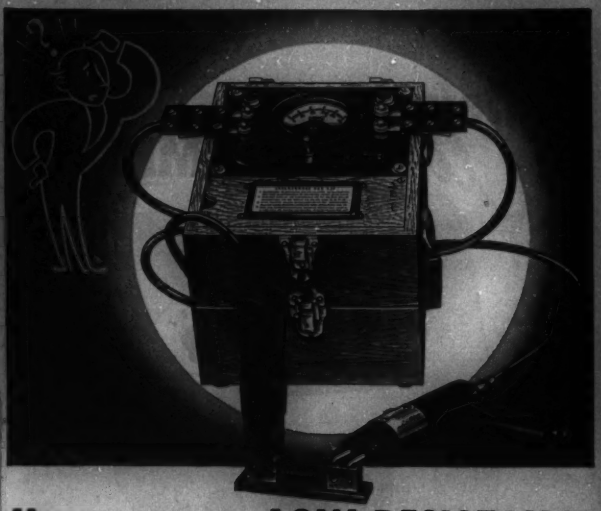

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. . . from 10 ohms to .00005 ohms

Need a quick, accurate method for testing bond or contact resistance against a predetermined low-resistance standard?

Shallcross Low Resistance Test Sets are available in a variety of portable and semi-portable types to facilitate the making of a large number of tests without the use of a bridge. Whether for production line testing of contact resistance of electrical equipment, or field testing of railway or aircraft bonding, they offer maximum efficiency and economy.

Shallcross Type 645 (illustrated) is completely self-contained and may be used either in a fixed position or suspended comfortably from the operator's shoulders for field work. A connection is made to one side of the bond or contact under test and the Pistol Grip Exploring Probe touched to the other side for a fast, accurate reading on the meter. Bar-to-bar commutator resistance measurements are as simple to make as a voltmeter reading.

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For Comparing Flux Density in Magnetic Fields

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against burnouts in industrial plants, power plants, wherever circuits must be safeguarded.

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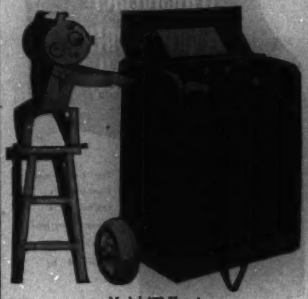

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Hypot is an easily movable unit on rubber-tired wheels. It enables one man to perform this service, protecting life and property. Has ample capacity for all circuit testing, with instantaneous reading on open scale from 0 to maximum voltage. Model 406 shown above: 3 KVA 0-3000-volt secondary, 115-volt 60-cycle primary, 500-milliampere secondary circuit. Comes complete with burning ground circuits. 20-foot high voltage leads, 50-foot input leads, 50-foot ground leads.

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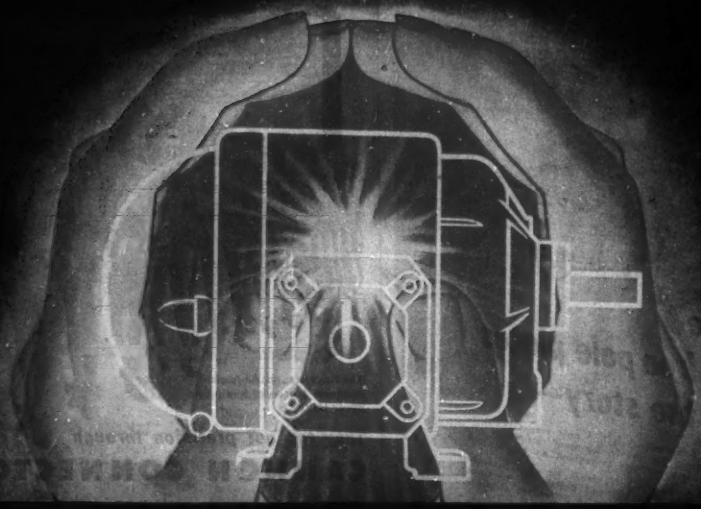

THE MISSING LINK IN HIGH TEMPERATURE PROTECTION IS HERE... DOW CORNING 993

Designers and manufacturers of electric motors and other electrical equipment can now provide better protection against overloads and higher temperatures by the use of the new #993 High Temperature Insulating Varnish—another Dow Corning Silicone product. Decreased size and weight of electrical equipment is possible if design limitations are based on insulating temperatures.

Dow Corning #993 Silicone Insulating Varnish is a natural complement to Fiberglas, mica, and asbestos for high temperature protection. It is inorganic in nature. It is the high temperature impregnating varnish that industry has been seeking.

In addition to the Dow Corning #993 Silicone Insulating Varnish we can supply Vartex Silicone Treated Fiberglas and Macallen Mica Products.

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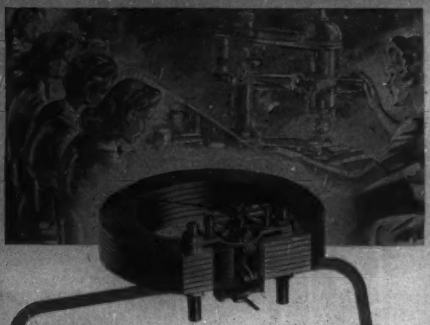

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Greater Accuracy—Soft iron pole pieces redistribute magnetic flux evenly. Simpson instruments provide accurate readings throughout an arc of 100°

Greater Strength—Pole pieces are used to anchor full bridges across top and bottom of movement. Moving assembly is locked in permanent alignment.

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Speed and Economy—Pole pieces are stamped, not machined. This is one of many ways Simpson has speeded construction, and lowered costs, of this basically better movement.

EXPERIENCE is a much used, and too often abused, word. Yet in any field experience is the only source of practical knowledge—the only sound basis for further advance.

Measured in terms of time alone, the experience of the Simpson organization is impressive enough. For more than 30 years this name has been associated with the design and manufacture of electrical instruments and testing equipment. But the real value of this experience is to be found in the many fundamental contributions Simpson has made to instrument quality.

The use of soft iron pole pieces in the patented Simpson movement serves as an example. An admittedly finer type of design, these soft iron pole pieces have been employed by Simpson to provide maximum strength as well as accuracy, and to achieve a simpler assembly that permits faster, more economical manufacture.

For today's vital needs, this experience enables Simpson to build "instruments that stay accurate" in greater volume than ever before. For your postwar requirements it will insure the correct interpretation of today's big advances.

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Many have asked us, particularly in recent years, "Where's the connection between 'CINAUDAGRAPH' and 'PERMANENT MAGNETS'?" There's a clue . . . in fact, two clues . . . as to the connection. Analyze our company name carefully and you'll get it.

Yes, our interest in permanent magnets goes back many years . . . back to a period when we manufactured electronic equipment and designed and made our own magnets. Thus, our knowledge of permanent magnets encompasses not only their design and manufacture but their application.

Today, as for some years past, our business is exclusively "PERMANENT MAGNETS." And much of the knowledge stored up has been set down in writing in the pamphlet illustrated below. If you are working on the design of magnets or are using them, you should have this information in your files. Send for your copy.

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Send for our pamphlet Permanent Magnet Design

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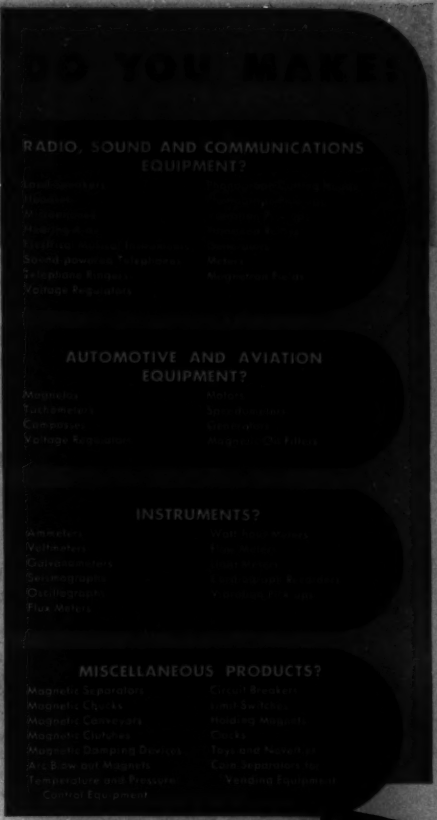

IF YOU make any of the above products, it will pay you to find out how *better permanent magnets* can improve efficiency and reduce costs. Put your design, development or production problems up to The Arnold Engineering Company. Arnold engineers have been of great assistance to many manufacturers and are at your service to advise exactly what Alnico permanent magnet will solve your particular problem.

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They knew, from experience, that slight changes in braid pattern made large variations in losses, and they were determined to find the one best pattern for each type of UHF cable. Using high-sensitivity instruments and other laboratory facilities that were unmatched at that time by any other manufacturer, they studied the effects of width of strand, the weaving angle, and the spacing between strands. After hundreds of tests, concentric-braid patterns which gave the lowest losses were devised.

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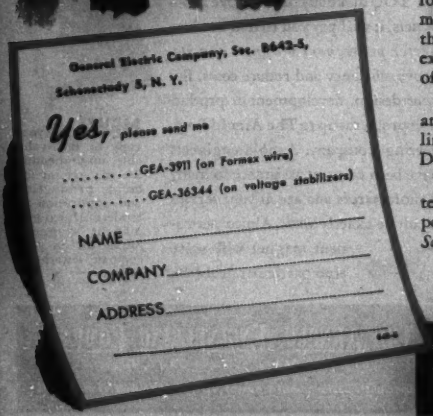
Whether you are designing new electronic equipment for television or for war weapons, you can't find a better starting point than G-E ultra-high-frequency cable. *General Electric, Schenectady, N. Y.*



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G-E Formex ribbon-rectangular magnet wire is available from four mils up to nine and one-half mils in thickness.

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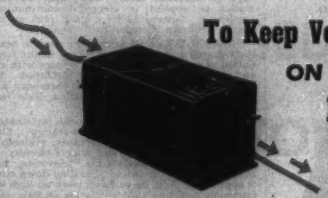

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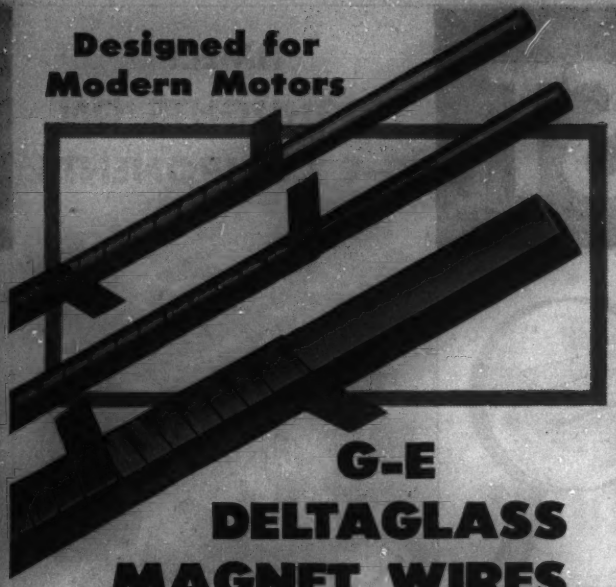

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Space factor is becoming increasingly more important in the selection of magnet wire because modern motors are designed to give the same power from smaller frames. Designing engineers of electrical products specify G-E Deltaglass Magnet Wire because it permits a greater amount of copper in the space allowed for the winding — and will still withstand the extra heat by a comfortable margin.

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Here's a catalog that will help solve your wiring problem. You can obtain your free copy by writing to Section Y-252-32, Appliance and Merchandise Dept., General Electric Co., Bridgeport, Conn. All Deltabeston Asbestos- Glass- and Synthetic-insulated Wires and Cables for special applications are distributed by Graybar Electric Co., G-E Supply Corp., and other G-E Merchandise Distributors.

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6. Circuits available: SPST Normally Open; SPST Normally Closed.

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with heater wound directly on blade

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Fully adjustable sensitive relay with 2000 ohm coil. Ideal for plate circuit or electronic applications. Minimum pull-in current only 2.6 milliamperes. SPST Contacts.
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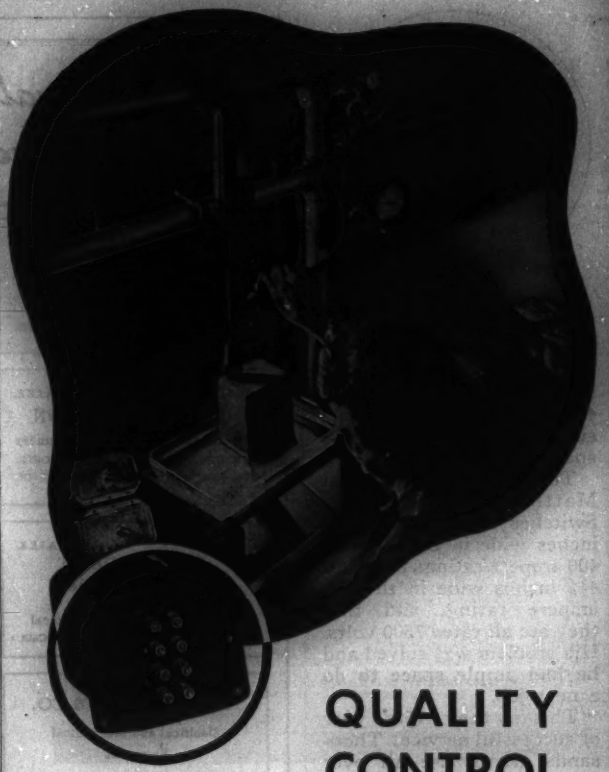

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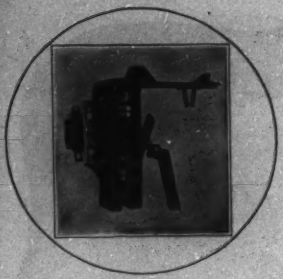

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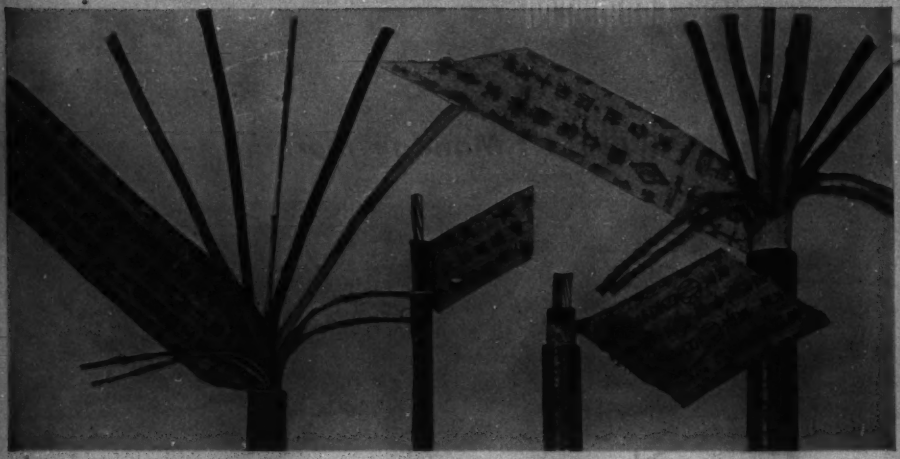

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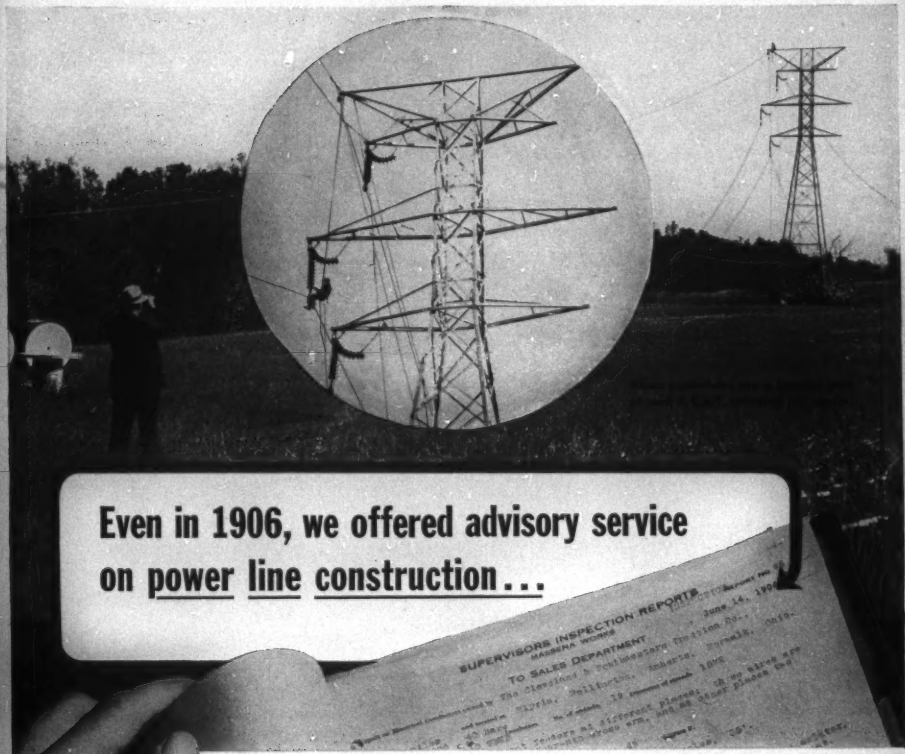

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